R-process nucleosynthesis during the decompression of neutron star crust material

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Abstract. About half of the nuclei heavier than iron observed in nature are produced by the so-called rapid neutron capture process, or r-process, of nucleosynthesis. The identification of the astrophysics site and the specific conditions in which the r-process takes place remains, however, one of the still-unsolved mysteries of modern astrophysics. The present contribution describes the r-process nucleosynthesis taking place during the decompression of neutron star crust material after its ejection from neutron star merger events and presents first consistent results based on relativistic hydrodynamics simulations. It includes the ejection not only of the inner crust but also of the outer crust, although essentially inner crust material can be expected to contribute significantly to the galactic enrichment. The nuclear mechanisms and the sensitivity of the final abundance calculation with respect to some nuclear physics inputs are described.

1. Introduction

The r-process, or the rapid neutron-capture process, of stellar nucleosynthesis is invoked to explain the production of the stable (and some long-lived radioactive) neutron-rich nuclides that are heavier than iron and observed in stars of various metallicities, as well as in the solar system (for a review, see [1]). In recent years nuclear astrophysicists have developed more and more sophisticated r-process models, trying to explain the solar system composition in a satisfactory way by adding new astrophysical or nuclear physics ingredients. The r-process remains the most complex nucleosynthetic process for modelling from the astrophysics as well as nuclear-physics points of view. The site(s) of the r-process has (have) not been identified yet, since all the proposed scenarios face serious problems. Complex—and often exotic—sites have been considered in the hope of identifying astrophysical conditions in which the production of neutrons is high enough to give rise to a successful r-process.

Progress in the modelling of type-II supernovae and γ-ray bursts has raised a lot of excitement about the so-called neutrino-driven wind environment. However, until now a successful r-process has not been obtained ab initio without tuning the relevant parameters (neutron excess, entropy, expansion timescale) in a way that is not supported by the most sophisticated existing models. Although these scenarios remain promising, especially in view of their potential to significantly contribute to the galactic enrichment [2], they remain handicapped by large uncertainties associated mainly with the still incompletely understood mechanism that is responsible for the supernova explosion and the persistent difficulties obtaining suitable r-process conditions in self-consistent dynamical explosion and neutron-star cooling models [3]. In addition, predictions of
the detailed composition of the ejected matter remain difficult owing to the remarkable sensitivity of r-process nucleosynthesis to uncertainties of the ejecta properties.

Early in the development of the theory of nucleosynthesis, an alternative to the r-process in high-temperature supernova environments was proposed [4]. It relies on the tendency of gravitationally bound, cool or cold matter in beta-equilibrium at high densities (typically $\rho > 10^{10} \text{ g cm}^{-3}$) to be composed of nuclei lying on the neutron-rich side of the valley of nuclear stability as a result of endothermic free-electron captures. The astrophysical relevance of this fact in accounting for the production of the r-nuclides has long been questioned. It remained largely unexplored until the study of the decompression of cold neutronized matter resulting from tidal effects of a black hole on a neutron star (NS) companion [5, 6]. Recently, special attention has been paid to NS mergers following the confirmation by hydrodynamic simulations that a non-negligible amount of matter can be ejected [7, 8, 9] and the confirmation that such material should be enriched in r-process nuclei [10, 11]. The ejection of initially cold, decompressed NS matter might also happen in other astrophysical scenarios like giant flares in soft-gamma repeaters, the explosion of a NS eroded below its minimum mass, or the equatorial shedding of material from very rapidly rotating supramassive or ultramassive NSs (see [1] for more details).

Recent three-dimensional simulations of NS–NS mergers have been performed using a general relativistic Smoothed Particle Hydrodynamics scheme [9, 12] with the Shen et al. equation of state [13]. Section 2 presents first nucleosynthesis results on the composition of the inner crust material ejected from a $1.35M_\odot–1.35M_\odot$ NS merger event. Although the outer crust is far less massive than the inner crust, the ejection of the inner crust cannot take place without at the same time leading to the ejection of at least some outer crust material. Section 3 presents the composition of the outer crust material in nuclear statistical equilibrium (NSE) at temperatures around $T = 8 \times 10^9 \text{ K}$, before and after its ejection to the interstellar medium.

2. Composition of the matter ejected from NS mergers

In the hydrodynamic simulation of a double $1.35M_\odot$ NS binary, about $3 \times 10^{-3} M_\odot$ of the system is found to become gravitationally unbound. The ejected “particles” (i.e., mass elements) originate essentially from the inner crust and more precisely from two different locations, i.e from layers at densities below and above roughly $0.3 \times \rho_S$ (where $\rho_S$ is the nuclear saturation density), as shown in the density histogram of Fig. 1. The former low-density set of surface particles is ejected through tidal forces without being much affected by the coalescence. In addition to these particles, when the NSs come into contact for the first time, some particles deeper in the inner crust are shocked and ejected perpendicularly to the orbital plane. These particles have a higher initial density ($\rho > 0.4 \rho_S$) than the crust particles ejected by tidal forces. Both these types of particles have a low initial electron fraction ranging between 0.015 and 0.050 (see Fig. 1 where about 45% of the mass is characterized by $Y_e = 0.015$). Note that for the first 27 ms, the density history is consistently followed by the numerical simulation. After that time, the determined ejecta escape the system and are assumed to expand with a constant velocity. In this case, the clump size increases linearly with time $t$ and consequently the particle density becomes proportional to $1/t^3$.

As far as the temperature history is concerned, most of the particles are heated during the ejection process to temperatures above 1 MeV. When heated to such temperatures, the composition of a particle is determined by NSE at given density and $Y_e$. At the time the drip density is reached, most of the ejected matter has cooled below 1 MeV (see Fig. 1, right panel) and the NSE has frozen out. As soon as the particle temperature has dropped below $10^{10}$ K, the particle composition, initially at NSE, is followed by a full network calculation and the temperature evolution is newly determined on the basis of the laws of thermodynamics allowing for possible nuclear heating through $\beta$-decays, fission and $\alpha$-decay processes, as described in [6].

The reaction network includes all 5000 species from protons up to Z=110 lying between the
Figure 1. Left: histogram representing the mass distribution of the ejected particles in different bins of initial density $\rho$ (relative to the saturation density $\rho_S \simeq 2.6 \times 10^{14}$ g/cm$^3$). Middle: same as the left panel for the electron fraction $Y_e$; Right: Same as the left panel for the temperature reached at the drip density $\rho_{drip} \simeq 4.2 \times 10^{11}$ g/cm$^3$.

Figure 2. Representation in the (N,Z) plane of the dominant fission regions. Nuclei for which spontaneous fission is estimated to be faster than $\beta$-decays are shown by full squares, those for which $\beta$-delayed fission is faster than the $\beta$-decays by open squares and those for which the neutron-induced fission is faster than the radiative neutron capture at $T = 10^9$ K by diamonds.

valley of $\beta$-stability and the neutron-drip line. All fusion reactions on light elements that may play a role when the NSE freezes out are included in addition to the radiative neutron captures and photodisintegrations. The reaction rates on the light species are taken from the NETGEN library, which includes all the latest compilations and evaluation of experimentally determined reaction rates [14]. Experimentally unknown reactions are estimated with the TALYS code [15] on the basis of the HFB-21 nuclear mass model [16]. On top of these reactions, fission and $\beta$-decay processes are also included, i.e neutron-induced fission, spontaneous fission, $\beta$-delayed fission, photofission, as well as $\beta$-delayed neutron emissions. The $\beta$-decay processes have been taken from the updated version of the Gross Theory [17] based on the HFB-14 $Q$-values, while all fission processes have been estimated on the basis of HFB-14 fission path and the full calculation of the corresponding barrier penetration [18]. The main fission region is illustrated in Fig. 2. The fission fragment distribution is taken from [19] and the fragment mass- and charge-asymmetry is derived from the HFB-14 prediction of the left-right asymmetry at the outer saddle point.

In this specific r-process scenario, the neutron density is initially so high ($N_n \simeq 10^{33} - 35$ cm$^{-3}$)
Figure 3. Left: Final abundance distribution of the matter ejected from the 1.35–1.35 $M_\odot$ NS merger as a function of the atomic mass. The distribution is compared with the solar r-abundance distribution (dotted circles). Right: time evolution of the charge number $\langle Z \rangle$, mass number $\langle A \rangle$ and temperature $\langle T \rangle$ mass-averaged over all the ejected particles.

that the nuclear flow follows for the first hundreds of ms a path licking the neutron drip line. For $Z \geq 103$, fission becomes efficient (Fig. 2) and recycling takes place two to three times before the neutrons are totally exhausted, as shown in Fig. 3 by the time evolution of the charge $\langle Z \rangle$ and mass number $\langle A \rangle$ mass-averaged over all the ejected particles. After several hundred ms, the density has dropped by a few orders of magnitude and the neutron density experiences a dramatic fall-off when neutrons get exhausted by captures. During this period of time, the nuclear flow around the $N = 126$ region follows the isotonic chain. When the neutron density reaches some $N_n = 10^{20}$ cm$^{-3}$, the timescale of neutron capture for the most abundant $N = 126$ nuclei becomes larger than a few seconds, and the nuclear flow is dominated by $\beta$-decays back to the stability line (as well as fission and $\alpha$-decay for the heaviest species). The average temperature remains rather low during the decompression, around 0.3–0.5 GK (Fig. 3), so that photoreactions do not play a major role.

The final mass-averaged composition of the ejected particles is shown in Fig. 3. The $A = 195$ abundance peak related to the $N = 126$ shell closure is produced in solar distribution and found to be almost insensitive to all input parameters, such as the initial abundances, the expansion timescales or the adopted nuclear models. In contrast, the second peak around $A = 140$ originates exclusively from the fission recycling, which is found to take place in the $A \simeq 280–290$ region at the time all neutrons have been captured. These nuclei are found to fission symmetrically, as seen in Fig. 3 by the $A \simeq 140$ peak corresponding to the mass-symmetric fragment distribution. It should be emphasized that significant uncertainties still affect the prediction of fission probabilities and fragment distributions, so that the exact strength and location of the $A \simeq 140$ fission peak depend on the adopted nuclear model. Improvement of the fission predictions represents a major challenge in this specific scenario.

3. Composition of the matter ejected from the outer crust

Although the outer crust (characterized by densities $\rho \leq \rho_{\text{drip}} \simeq 4.2 \times 10^{14}$ g/cm$^3$) is far less massive than the inner crust, the ejection of the inner crust cannot take place without at the same time leading to the ejection of at least some outer crust material. The whole outer crust typically amounts to $10^{-5}$ to $10^{-4}$ $M_\odot$, depending on the NS mass and radius [20], so that its contribution even for complete ejection remains negligible compared to the $10^{-3}$ to $10^{-2}$ $M_\odot$ of
the inner crust material ejected during a NS–NS merger event. Still, we have estimated the composition of the outer crust material initially heated to NSE at a temperature of about $10^{10}$ K before and after the decompression that follows its ejection. Note that the amount of unbound outer crust material and the dynamics of its ejection cannot be reliably calculated from the hydrodynamic model. Details about the adopted decompression model can be found in [21].

Before decompression and at temperatures corresponding to $8\times 10^9$ K, the Coulomb effect due to the high densities in the crust leads to an overall composition of the outer crust in neutron-rich nuclei with a mass distribution close to the solar system r-abundance distribution, as shown in Fig. 4 (Left panel). Such distributions differ, however, from the solar one due to a shift in the second peak to lower mass numbers. During the decompression, the free neutrons (initially liberated by the high temperatures) are re-captured leading to a final distribution of stable neutron-rich nuclei with a mass distribution of $80 \leq A \leq 140$ nuclei in excellent agreement with the solar distribution, provided the outer crust is initially at a temperature around $8 \times 10^9$ K and all layers of the outer crust are ejected. The decompression of the outer NS crust provides suitable conditions for a robust r-processing of the light species, i.e. r-nuclei with $A \leq 140$. The final composition should carry the imprint of the temperature at which the NSE is frozen prior to the ejection. Such temperatures typically around $8\times 9 \times 10^9$ K correspond to those at which NSE can be dynamically achieved in cooling events [21].

Uncertainties in the nuclear physics input can influence the calculation of the final abundances. In particular, the exact strength, location, and width of the $N = 50$ and $N = 82$ r-process peaks are sensitive to the mass model adopted, as shown in Fig. 4 (right panel), where three different mass models are considered, namely HFB-19, HFB-21 [16] and D1M [22]. The production of the $90 < A < 120$ r-nuclei can also be significantly affected. The importance of nuclear masses in this specific r-process nucleosynthesis scenario is essentially linked to the initial NSE conditions, which define not only the most abundant species initially present in the outer crust, but also the amount of free neutrons available for the neutron-capture process during the decompression. In contrast, the impact of uncertainties affecting the $\beta$-decay rates is rather limited, though $\beta$-delayed neutron emission plays some role in smoothing the final abundance pattern. More details can be found in [21].

4. Conclusions

Most of the problems in understanding the origin of r-process elements are related to our ignorance of the astrophysical site that is capable of providing the required large neutron flux. In this respect, explaining the production of r-process elements is essentially an astrophysics issue that will require improved hydrodynamic models to shed better light on possible scenarios. Different sites have been proposed, with neutrino-driven outflows during supernova or $\gamma$-ray burst explosions being the currently most popular ones, but facing severe difficulties concerning exact conditions and robustness. Here we have shown that decompressed NS matter is an extremely promising source. In particular, it provides suitable conditions for a robust r-processing. The resulting r-abundance distribution is very similar to the solar one, at least for $A > 140$ nuclei from the inner NS crust. Nuclei with $A < 140$ with solar distribution could originate from the outer crust, but the amount of such matter is very small. The underlying nuclear mechanisms differ significantly from those at action in in supernova scenarios, in particular fission plays a major role in recycling heavy material. The similarity between the predicted and solar abundance patterns as well as the robustness of the prediction against variations of input parameters make this site one of the most promising that deserves further exploration concerning various aspects such as nucleosynthesis, hydrodynamics, and galactic chemical evolution. From the nuclear point of view, this site also implies a new challenge, since it involves the production of neutron-drip nuclei, for which $\beta$-decay, neutron capture and fission rates need to be determined.
**Figure 4.** Left: Abundance distribution of the whole outer crust material when initially heated to NSE at a temperature of \( T = 8 \times 10^9 \) K. The calculation was performed with the HFB-19 masses [16] when experimental masses are not available. The distribution is compared with the solar r-abundance distribution (open circles). Middle: Same as the left panel, after ejection of the outer crust. Right: Same as the middle panel for three different mass models (and corresponding reaction rates) [16, 22]. Experimental masses are used whenever available.

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