Coalescing Neutron Stars: A Solution to the R-Process Problem?

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1.1 Introduction

Most recent nucleosynthesis parameter studies \cite{3, 4, 11} place questions on the ability of high entropy neutrino wind scenarios in type II supernovae to produce r-process nuclei for $A < 110$ in correct amounts. In addition, it remains an open question whether the entropies required for the nuclei with $A > 110$ can actually be attained in type II supernova events. Thus, an alternative or supplementary r-process environment is needed, leading possibly to two different production sites for r-process nuclei: a high entropy, high $Y_e$ (neutrino wind in type II supernovae) and a low entropy, low $Y_e$ (decompression of neutron star (ns) material) scenario.

Further indications for a production site possibly different from SN II arise from observations of low metallicity stars \cite{9}. It seems that the production of r-process nuclei is delayed in comparison with the major SN II yields, a fact that would be consistent with the merging scenario of two neutron stars.

The tidal disruption of a ns by a black hole and possible consequences for nucleosynthesis has first been studied by Lattimer and Schramm \cite{6, 7}, the merging of a neutron star binary has been discussed by Symbalisty and Schramm \cite{16}. The related decompression of the neutron star material has been investigated by Lattimer et al. \cite{5}, Eichler et al. \cite{2}, who also discussed various other aspects of such a merging scenario, and by Meyer \cite{10}. In the context of numerical simulations the merging event nucleosynthesis has been discussed by Davies et al. \cite{1} and by Ruffert et al. \cite{15}.

1.2 The Calculations

To investigate the possible relevance of neutron star mergers for the r-process nucleosynthesis we perform 3D Newtonian SPH calculations of the hydrodynamics of equal (1.6 $M_\odot$ of baryonic) mass neutron star binary coalescences. Starting with an initial separation of 45 km we follow the evolution of matter for 12.9 ms. We use the physical equation of state of Lattimer and Swesty \cite{8} to model the microphysics of the hot neutron star matter. To test the sensitivity of our results to the chosen approaches and approximations we perform in total 10 different runs where we test each time the sensitivity to one property of our model \cite{14}. We vary the resolution ($\sim 21000$ and $\sim 50000$ particles), the equation of state (polytrope), the artificial viscosity scheme \cite{12}, the stellar masses (1.4 $M_\odot$ of baryonic matter), we include neutrinos (free-streaming limit), switch off the gravitational backreaction force, and vary the initial stellar spins. In addition we test the influence of the initial configuration, i.e. spherical stars versus corotating equilibrium configurations.
1.3 Results

We find that, dependent on the initial spins and strongly dependent on the EOS, between $4 \cdot 10^{-3}$ and $4 \cdot 10^{-2}$ $M_\odot$ become unbound. Assuming a core collapse supernova rate of $2.2 \cdot 10^{-2}$ (year galaxy)$^{-1}$ [13], one needs $10^{-6}$ to $10^{-4}$ $M_\odot$ of ejected r-process material per supernova event to explain the observed abundances if type II supernovae are assumed to be the only source. The rate of neutron star mergers has recently been estimated to be $8 \cdot 10^{-6}$ (year galaxy)$^{-1}$ (see [17]). Taking these numbers, one would hence need $\sim 3 \cdot 10^{-3}$ $M_\odot$ to $\sim 0.3$ $M_\odot$ for an explanation of the observed r-process material exclusively by neutron star mergers. Thus our results for the ejected mass from $4 \cdot 10^{-3}$ to $3 - 4 \cdot 10^{-2}$ $M_\odot$ look very promising (see Figure 1).

As a first step we use the mean properties of all ejected particles (initial corotation) for an r-process calculation. We adopt the following approach: in the very first expansion phase (where $\rho > \rho_{\text{drip}} \approx 4 \cdot 10^{11}$ g cm$^{-3}$) we use the abundances of neutrons, protons, alphas and a representative nucleus provided by the LS-EOS. When the density drops below $\rho_{\text{drip}}$ we switch over to a treatment of individual nuclei with a full r-process network following all reactions like neutron capture, photo-disintegrations, $\beta$-decays etc. as discussed in Freiburghaus et al. [4]. Since the representative nucleus at $\rho_{\text{drip}}$ was too neutron rich ($(Z, A) = (26, 155)$), we took the most neutron rich nucleus in the network ($(Z, A) = (26, 73)$) and assumed the

![Figure 1: The shaded region shows the amount of ejecta found in our calculations. The circle shows the amount of ejecta needed per event if SN II are assumed to be the only sources of the r-process. The asterisk gives the needed ejecta per merging event for the rate of Narayan et al. (1991), the cross for the estimate of van den Heuvel and Lorimer (1996). The event rate is given in year$^{-1}$ galaxy$^{-1}$, the ejected mass in solar units.](image-url)

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remaining neutrons to be free. Following the trajectory given by the hydro calculation (extrapolation for \( t > 12.9 \) ms) we obtained the abundance pattern that is shown in Figure 2 together with the observed r-process abundances.

![Abundance pattern graph](image)

Figure 2: Comparison of the r-process calculations for a corotating system (initial corotation; line) with the observed abundances (crosses).

The observed features of the abundance pattern in the range \( 125 < A < 200 \) are well reproduced. Especially the peak around \( A = 195 \) is easily reproduced without any tuning of the initial entropy.

This approach has two shortcomings: (i) as long as the LS-EOS is used, only one (representative) nucleus is used instead of an ensemble of nuclei and (ii) weak interactions such as \( \beta \)-decays or \( e^- - e^+ \), \( e^- \) captures on protons and neutrons are disregarded in this early phase. For the case of initial corotation this approximation might not be crucial since the ejecta essentially stay cold (until perhaps, at later times, heating by \( \beta \)-decays sets in). For different initial spins, however, weak interactions might change the \( Y_e \) of the composition in this early phase.

Clearly, in future investigations these aspects have to be treated in more detail.

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