Nucleosynthesis Calculations for the Ejecta of Neutron Star Coalescences

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We present the results of fully dynamical r-process network calculations for the ejecta of neutron star mergers (NSMs). The late stages of the inspiral and the final violent coalescence of a neutron star binary have been calculated in detail using a 3D hydrodynamics code (Newtonian gravity plus backreaction forces emerging from the emission of gravitational waves) and a realistic nuclear equation of state. The found trajectories for the ejecta serve as input for dynamical r-process calculations where all relevant nuclear reactions (including beta-decays depositing nuclear energy in the expanding material) are followed.

We find that all the ejected material undergoes r-process. For an initial $Y_e$ close to 0.1 the abundance distributions reproduce very accurately the solar r-process pattern for nuclei with $A > 130$. For lighter nuclei strongly underabundant (as compared to solar) distributions are encountered. We show that this behaviour is consistent with the latest observations of very old, metal-poor stars, despite simplistic arguments that have recently been raised against the possibility of NSM as possible sources of Galactic r-process material.

1. Hydrodynamic Calculations of Neutron Star Coalescences

The possible impact of merging neutron stars for r-process nucleosynthesis has been realized many years ago \cite{1-4}. To quantify this issue we have performed detailed hydrodynamic studies of the last inspiral stages and the final coalescence of neutron star binary systems. We used the smoothed particle hydrodynamics method to solve the hydrodynamic equations coupled with the nuclear equation of state of Lattimer and Swesty (\cite{5}; LS-EOS). To resolve shocks accurately a largely improved, hybrid artificial viscosity scheme \cite{6} that profits from two recently suggested modifications of the 'standard scheme' \cite{7,8} has been applied. Gravitational forces are evaluated efficiently using a binary tree \cite{9}. The backreaction forces resulting from the emission of gravitational waves are accounted for in the quadrupole approximation of point masses \cite{10,6}. For further details and test calculations we refer to \cite{10,6}.

To explore the possible range of outcomes depending on the physical parameters of neutron star binary systems a variety of different initial configurations has been examined. For example, binary systems -symmetric and asymmetric ones- with six different initial spin combinations and three different neutron star masses ($1.3$, $1.4$ and $1.6 \, M_\odot$) have been...
investigated.
In all of these cases between $\sim 4 \cdot 10^{-3}$ and $\sim 4 \cdot 10^{-2} \, M_\odot$ were ejected into space. Folded with the estimates for the event rate of $\sim 10^{-5}$ per year and galaxy [11–13], this amount could contribute substantially to the enrichment of the Galaxy with heavy elements, provided that the ejecta contain large amounts of r-process nuclei.

2. Fully dynamical r-process Network Calculations

To clarify issue of the abundances within these ejecta, we have taken the history of a blob of ejected material located in a rapidly expanding spiral arm from our best resolved calculation (a corotating binary system) as a starting point for the network calculations. For two reasons $Y_e$ is treated as a free parameter in these calculations. First, with the current resolution of our 3D-calculations we cannot follow closely enough the steep density gradients in the thin, but rather proton rich neutron star surface, that determine the initial $Y_e$ via the beta-equilibrium condition $\dot{\mu} = \mu_e(Y_e)$. Second, $Y_e$ evolves during the coalescence process by means of weak interactions. Thus all the relevant weak interaction processes and neutrino transport should be included, which is currently not the case. We started our nucleosynthesis calculations at a point where the density dropped below the neutron drip density. Above this density all beta-decays are Pauli-blocked and thus the material cools adiabatically during the rapid expansion. Along the expansion trajectory of the ejected matter blob all relevant nuclear reactions including beta-decays have been followed [14]. The temperature history within the ejecta is determined by the interplay of cooling due to the rapid expansion and the heat input from the decaying nuclei. To ensure
that results are not influenced by possibly artificially high numerical temperatures, we also performed test calculations starting exclusively with neutrons and protons at an artificially low temperature ($T = 10^{-2}$ MeV). In this case the almost immediate recombination of the nucleons into $\alpha$-particles heated up the material to r-process-like temperatures on extremely short time scales [14].

In all investigated cases r-process took place, and the initial $Y_e$ turned out to be the decisive parameter that determined the resulting abundance distribution. For $Y_e$-values too large or too small the abundance peaks were shifted towards those of the s-process, for $Y_e$ close to 0.1 the solar abundances above $A > 130$ are very closely reproduced. Isotopes with $A < 130$ very largely underabundant compared to the solar values.

3. Discussion

Despite recent progress in the questions related to the nucleosynthetic impact of neutron star mergers uncertainties remain:

- **EOS**: While matter properties at subnuclear densities seem to be reasonably well understood, the high density regime, where exotic nuclear states are expected to appear, remains rather uncertain. We found that the stiffness of the neutron star EOS has a dramatic effect on the amount of ejected material. For example, a corotating binary system following the rather stiff LS-EOS releases $\sim 4 \cdot 10^{-2}$ M$_\odot$ in the tips of the emerging spiral arms, while for a similar system governed by a $\Gamma = 2.0$-polytrope does not show any resolvable mass loss [11]. Test runs with polytropes of density dependent stiffness revealed that it is unfortunately the poorly known high density regime that determines the amount of ejected material. Therefore, if the nuclear matter at high density should be softer (stiffer) than the LS-EOS less
(more) material should become unbound. Most recent EOSs \[^{15,16}\] are rather stiff and therefore support the results found with the LS-EOS.

- **Gravity**: A neutron star binary is unquestionably a highly relativistic system. Thus, using (basically) Newtonian gravity can only be a first approach for the exploration of the system dynamics. Recently, progress has been made using approximations to full GR (e.g. \[^{17-19}\]). One might suspect the stronger gravity forces of GR to reduce the amount of ejected material. However, this point will have to be clarified by further studies with a sophisticated gravity treatment and the relevant microphysics input.

- **Weak interactions and neutrino transport**: As has been shown, the initial $Y_e$ of the ejected material plays a crucial role in determining the resulting abundances of the ejected material. To improve on this aspect of the problem first of all higher resolution is needed to resolve the low density neutron star crust with its higher $Y_e$ values. In addition the weak interaction physics (including neutrino transport) has to be incorporated consistently as well as efficiently to predict the evolution of $Y_e$ during the coalescence and ejection process.

Despite these uncertainties it has to be stated that if EOS and gravity allow for the ejection of non-negligible amounts of material and $Y_e$ is close to 0.1, which is a very reasonable value for neutron star material, neutron star mergers will contribute r-process nuclei in solar abundances for nuclei with $A > 130$ and strongly underabundant amounts of nuclei with $A < 130$. This is in excellent agreement with recent observations of metal-poor stars \[^{23,24}\] that show a remarkable concordance of heavy r-process nuclei with scaled solar r-process abundances that breaks down for nuclei below $A \approx 130$.

Recently, observations of metal-poor stars have been used to argue against the possibility of NSMs as substantial sources of Galactic r-process material \[^{20}\]. On average, each volume of the interstellar medium containing $\approx 3 \times 10^4 M_\odot$ is enriched by $10^3$ supernovae (SNe) in order to obtain solar metallicities. On the other hand, the typical mass of the interstellar medium (ISM) into which the ejecta of an SN remnant are mixed (before the remnant shock is quenched) is of the order $3 \times 10^4 M_\odot$ as well. Thus, if the r-process would originate from SNe, the abundances in the affected ISM resulting from a single SN event in prior unpolluted regions would amount to $(r/H)_{SN} \approx 10^{-3} (r/H)_\odot$. Since NSM rates are lower than SN rates by approximately three orders of magnitude this ratio would in the case of a NSM origin be 0 in unpolluted ISM and close to solar in matter which experienced NSM ejecta, provided that the mass of the mixed ISM is similar to SN remnants. Such behaviour is not observed in low metallicity stars and therefore NSMs would be ruled out as candidate sites for the r-process.

The arguments raised in \[^{20}\], however, are too simplistic since they omit two important aspects. (1) The amount of NSM ejecta mixing with the ISM is not clear (total energetics and ring-like rather than spherical ejection). (2) The more important point is that the low-metallicity observations measure the abundances in individual stars rather than in mixed remnants. Only if the same mass would be swept up and if stars would form from fully mixed regions the above argument against NSMs holds. The mixing process of elemental yields from core collapse supernovae with the ISM has recently been simulated with a 3D
stochastic model in order to understand the evolution of the scatter in [element/Fe] ratios
during the history of the Galaxy [21]. According to this work the mixing proceeds via
the following stages: for [Fe/H] < −3.0 (corresponding to a Galactic age of ∼ 200 Myrs;
[21] Fig. 6) the ISM is not mixed, but rather dominated by local inhomogeneities leading
to a very large scatter in the observed abundances of individual stars, in agreement with
observations. For [Fe/H] > -2.0 (∼ 1500 Myrs) the ISM is well-mixed (small scatter in
observations), inbetween a continuous transition between both regimes is encountered. It
could also be shown that a stochastic choice of star formation can lead to much smaller
metallicities than expected from a well mixed remnant. For events which occur with a much
smaller frequency (like NSM) this mixed phase should be delayed to larger metallicities.
In addition, one expects with the large amounts of r-ejecta from NSMs a much larger
scatter than for SNe. Both effects are seen in the r/Fe observations (a scatter of more
than a factor of 100 at low metallicities which still amounts to a factor of 10 at [Fe/H]=-1,
see Fig. 2 in [22]). This fact combined with the suppression of abundances below A=130
in low-metallicity stars, can be taken as supportive features to a fission cycling r-process
from a low frequency source such as NSMs. Galactic evolution calculations as in [21]
are needed in order to test the expected amount of scatter as a function of metallicity.

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