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Synthesis of Heavy Elements in the Ejecta of Neutron Star Mergers

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Abstract. We present a nucleosynthesis study on the neutrino-driven wind after neutron star merger. Post-processing tracers from a hydrodynamical simulation, we determine nucleosynthesis yields that depend on both life time of the massive neutron star and polar angle. In comparison with the dynamic ejecta we find a complementary nucleosynthesis, which can explain the r-process pattern beyond the first r-process peak. Additionally, we predict possible forms of light curves for the detection of a kilonova.

1. Introduction

The merger of two neutron stars has been recognized as a possible site for the rapid neutron capture process (r-process) for a long time [1, 2]. Being a both neutron-rich and explosive environment, even the heaviest elements up to uranium can be produced. Further evidence for the r-process in mergers is provided by the detection of a near-infrared excess in the afterglow several days after a short gamma-ray burst (sGRB) [3, 4], which has been interpreted as a "kilonova" [5]. Since here substantial mass fractions of r-nuclei decay radioactively, the resulting heating rate powers this electromagnetic transient. It can serve as a valuable counterpart [6] in coincidence with detecting gravitational waves (GWs), emitted by such systems.

At least three different kinds of ejected matter can be distinguished [7]: dynamic ejecta due to gravitational torques and hydrodynamical processes, neutrino-driven winds, and viscously driven material by the late-time disk dissolution. In this proceeding, we focus on the neutrino-driven wind and its interplay with the dynamic ejecta.

2. Method

Our nucleosynthesis study is based on the first three-dimensional, long-term ($t_{\rm sim} \approx 190$ ms), Newtonian simulation of a central massive neutron star (MNS) surrounded by a thick accretion

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disk with an initial mass of $M_{\rm disk} \approx 0.19 M_\odot$ (for further details see [8]). Neutrino-matter interactions are modeled with a spectral neutrino leakage scheme, taking into account neutrino absorption. To calculate nucleosynthesis yields, we use tracer particles that are advected passively. The tracers are distributed proportional to the density in the beginning. Throughout the simulation, every tracer records the temporal profile of ejected material, in particular density, internal energy, electron fraction and velocity. These data are post-processed with a full nuclear reaction network [9] including neutrino absorption on nucleons. We determine heating rates by computing the energy generation by nuclear reactions, which essentially originates from beta-decays. Over 17000 unbound tracers are used to compute total masses, defined as the sum over the final mass fraction distributions times the mass of all tracers [10].

3. Results

Both amount and composition of matter ejected in the neutrino-driven wind depend on the evolution of the accretion disk and the life time of the MNS. This dependence is explored in Fig. 1, showing the unbound mass as a function of the electron fraction and time.

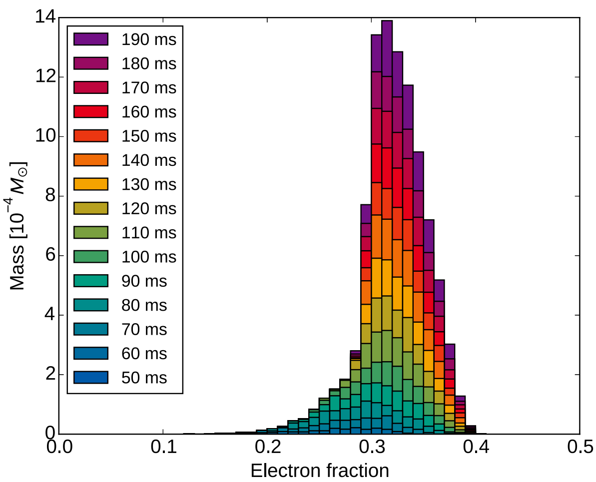

Figure 1. Electron fraction distribution of the ejected mass at different simulation times. Y_e covers values from 0.2 to 0.4 with a final average of $Y_e \sim 0.33$. Very few material with $Y_e < 0.3$ is ejected within the first 100 ms. From 110 ms on, the growth rate of unbound mass becomes roughly constant, as the substantial mass accretion rate inside the disk leads to quasi steady-state conditions with neutrinos as major cooling source. Therefore, neutrino interaction rates tend to approach equilibrium. In total, material in excess of up to $9 \cdot 10^{-3} M_\odot$ ($\sim 5\%$ of $M_{\rm disk}$) becomes unbound until 190 ms after the merger.

In the neutrino-driven wind mainly nuclei with $A < 130$ are produced, i.e. lighter heavy elements. This distribution is a direct consequence of the key parameter Y_e. The left panel of Fig. 2 shows the total masses for different simulation times (colored lines). Heavy nuclei beyond the second r-process peak ($A \sim 130$) form in nearly negligible amounts at early times only, as it is apparent by the overlap of the three curves. Similar to [11], we find a threshold of $Y_e \approx 0.25$ beyond which no more r-process elements are created. Considering complete mixing with the dynamic ejecta [12] that feature a robust strong r-process due to fission cycling (black line in the right part of Fig. 2), the whole r-process mass fractions are formed from the first peak ($A \sim 80$) to the third peak ($A \sim 195$). The combined pattern is compatible with the solar r-process abundances [13] as well as the abundances in the oldest r-process enriched stars [14].

While full mixing occurs, e.g., on a time scale of star formation, these two types of ejecta are well separated in the direct aftermath of a merger. This initial separation has important implications for the possible detection of a kilonova. Using a semi-analytical model [15], we calculate the resulting combined light curves in four different angular bins (see right panel of Fig. 2). The light curves peak in all directions after ~ 4 h, caused by the decay of nuclei with $A \sim 80$. Furthermore, there is a second peak $3-4$ d later in the last two angular bins closest to the disk, originating from larger mass fractions of the heavy r-process ejecta. Due to their relatively high opacities of roughly 10 cm^2/g [16] the medium becomes delayed transparent when the temperature has decreased (while rapidly shifting the light curve to the infrared wavelengths).

The shapes of the combined light curves significantly depend on the observation angle. This anisotropy needs to be taken into account when assessing the detectability of optical counterparts for neutron star mergers.

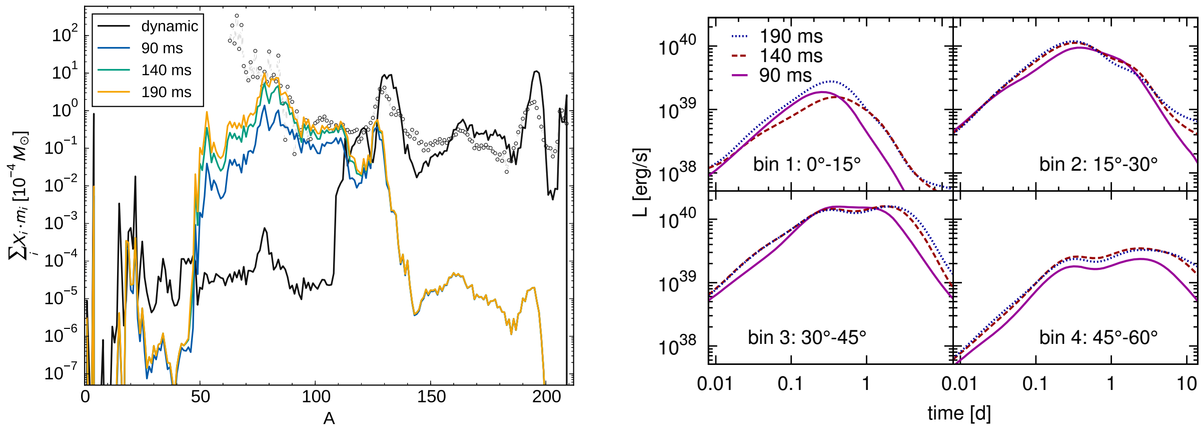

Figure 2. Left: comparison of the nucleosynthesis yields for neutrino-driven wind at three different simulation times and dynamic ejecta. Solar abundances are shown with dots for comparison. Right: contributions of the combined ejecta to the luminosity in the angular bins.

4. Conclusions

We have shown that neutrino-driven wind ejecta play a relevant role in the nucleosynthesis of neutron star mergers and it is crucial to disentangle the interplay of the different ejecta. Further detailed simulations (e.g. in general relativity [17, 18]), observations that constrain r-process abundances, and nuclear physics experiments advancing toward the most neutron-rich nuclei will help to pin down the role of mergers for the origin of the heavy elements in the universe.

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