The r-process in black hole–neutron star mergers based on a fully general-relativistic simulation

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Abstract. We investigate the black hole–neutron star binary merger in the contest of the r-process nucleosynthesis. Employing a hydrodynamical model simulated in the framework of full general relativity, we perform nuclear reaction network calculations. The extremely neutron-rich matter with the total mass $0.01 M_\odot$ is ejected, in which a strong r-process with fission cycling proceeds due to the high neutron number density. We discuss relevant astrophysical issues such as the origin of r-process elements as well as the r-process powered electromagnetic transients.

1. Introduction

The astrophysical origin of the r-process elements, half the elements heavier than iron including actinides, gold, europium, etc., is still shrouded in mystery despite more than half a century of studies [1]. Although the proto-neutron-star wind scenario has been considered to be the most likely site, recent state-of-the-art hydrodynamic simulations suggest serious problems to achieve the appropriate physical conditions for the r-process. Core-collapse supernovae, therefore, appear to be excluded as the main sources of the r-process elements (but of those with $A \lesssim 110$ produced by a weak r-process [2, 3]). Besides standard supernova scenarios, some others such as magnetic-jet explosions [4, 5] and those induced via the quark-hadron phase transition [6] have been proposed as possible alternatives.

Mergers of compact object binaries, consisting of double neutron stars (NS-NS) or a black hole and a neutron star (BH-NS), have also been investigated in the context of the r-process origin. Recent nucleosynthetic works [7, 8, 9], however, are based on the hydrodynamical simulations in the framework of particle-based SPH simulations assuming Newtonian or approximative general-relativistic gravity. This paper presents the first r-process study with the use of the hydrodynamical result based on a three-dimensional, full general relativistic treatment. We focus on a BH-NS merger as an initial attempt, which ejects extremely neutron-rich matter via the tidal disruption of the neutron-star material.

2. Neutron-rich ejecta from the BH-NS merger

The hydrodynamical simulation, used in this study, has been performed based on a 3D general relativistic code [10, 11]. This code adopts a tabulated, temperature-dependent equation of
Figure 1. Dynamics of the BH-NS merger. Snapshots of the density distribution are shown in the region of $(400 \text{ km})^2$. The color range (in the log scale) corresponds to $10^5 - 10^{15} \text{ g cm}^{-3}$.

state of nuclear matter [12] and applies a simplified treatment of neutrino transport including the neutrino cooling via the leakage scheme. We study the BH-NS merger model that initially consists of a non-rotating $4.05 M_\odot$ black hole and a $1.35 M_\odot$ neutron star. The amount of ejecta is estimated to be $0.01 M_\odot$ from the hydrodynamical simulation.

The dynamics of the BH-NS merger is seen in Figure 1, illustrating time slices of the density evolution on the orbital plane. The matter is ejected mainly by the tidal disruption of the neutron-star material. At the coalescence (0 ms), the neutron star is revolving around the black hole with the orbital separation of $60 \text{ km}$. In the next snapshot (4 ms), we observe the neutron star tidally disrupted along with the orbital motion by the strong gravity of the black hole. The disrupted matter falls into the black hole and partially forms an accretion disk except for that having the velocity higher than the escape velocity from the remnant black hole (13 ms).

3. The r-process nucleosynthesis

The ejecta of the BH-NS model is extremely neutron-rich as shown in the left panel of Figure 2. The histogram has the peak at $Y_e \sim 0.05$, which qualitatively agrees with previous hydrodynamical studies. Here, the $Y_e$ distribution of the ejecta is evaluated on the two-dimensional orbital plane for simplicity. The ejection is mainly due to the tidal disruption of the neutron-star material without strong shock heating which induces positron-capture on neutrons and increases $Y_e$. We compute the nuclear abundance evolutions using a reaction network described in [2] applying the thermodynamic trajectories deduced from these ejecta. The network follows the temporal evolutions of density and temperature for each trajectory with the initial $Y_e$. The network adopts the JINA-REACLIB compilation [13] for experimental rates, the BRUSLIB compilation [14] for theoretical rates, and the HFB-14 fission barriers.

We select two representative thermodynamic trajectories with $Y_e = 0.01$ and 0.04 (a full set of calculations will be presented elsewhere). The nucleosynthetic results are presented in Figure 3 that shows the nuclear abundances with the solar-system r-process distribution. A strong r-process proceeds and produces the elements from the 2nd peak to the 3rd peak and actinides. The two results are almost identical as a consequence of the r-process via strong fission cycling. According to this result, the total ejecta is expected to have a similar abundance distribution to that in Figure 3, in which the light r-process elements ($A < 130$) are severely underproduced.

4. Discussion

We performed r-process calculations with the use of a general relativistic BH-NS merger simulation. Two representative thermodynamic trajectories on the orbital plane were chosen for nucleosynthesis. The r-process proceeded strongly and produced the heavy abundances with
Figure 2. Distribution of $Y_e$ of ejecta. The mass fraction for each $Y_e$-bin ejecta is plotted in the logarithmic scale.

Figure 3. Nuclear abundances for two selected tracer particles of $Y_e = 0.01$ and 0.04.

$A > 130$ only. Therefore, the dynamical ejecta from BH-NS mergers may not be the unique sources of the r-process elements but other contributions from the subsequent accretion tori or from NS-NS mergers to account for the full-range of the solar system r-process pattern [15].

NS-NS and BH-NS mergers are expected to be the sources of the r-process powered electromagnetic transients (“kilonovae” or ‘r-process novae”), being associated with short gamma-ray burst and gravitational-wave events. Detailed nucleosynthetic studies relevant for mergers will be important not only for galactic chemical evolution but also for the gamma-ray and gravitational-wave astronomy. The large ejected mass of 0.01 $M_\odot$ in our BH-NS model may be favorable to account for the brightness of the recently detected (possible) kilonova [16, 17].

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