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Recipe to Reproduce the Solar System R-Process Abundances

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The astrophysical site for the r-process has not yet been uniquely identified. Neutron star mergers (NSMs) have recently received special attention as production sites for the r-process. The ejected matter from the NSMs is extremely neutron-rich ($Y_e < 0.1$) and the r-process path proceeds along the neutron drip line and enters the region of fissile nuclei. In this situation, theoretical models of nuclear masses and fission modes are quite important. In this study, we carry out r-process nucleosynthesis simulations in NSMs based upon recent numerical simulations. We here constructed a nuclear reaction network code and utilize a new model for nuclear masses and a fission fragment distributions. In our nucleosynthesis simulations the final r-process elemental abundances exhibit a very flat distribution for $A = 90 - 180$. This due to the fact that several fission cycles occur in the extremely neutron-rich conditions of NSMs. Combining these results with magneto-rotationally driven core-collapse supernovae (CCSNe) that predict successful r-process abundance peaks at $A \sim 130$ and 195, we find that NSMs can resolve the underproduction problems of such CCSN models for the isotopes just below and above the abundance peaks. We discuss the relative contributions to the solar-system r-process yields from CCSNe and NSMs.

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1. Introduction

Compact binary mergers (CBMs) are expected to be sources of both gravitational waves (GWs) and electromagnetic radiation. Their GWs should be detectable in future observatories such as Advanced LIGO, Advanced Virgo, and KAGRA. Once discovered, such signals could provide valuable information about the properties of extremely dense matter such as the equation of state, the radii of neutron stars, and the event rates of CBMs. Moreover CBMs are candidates for short gamma-ray bursts (GRBs) although the details of their central engine are still not fully understood. Their electromagnetic signals should be observable not only in gamma-rays, but also in other electromagnetic bands [1]. Electromagnetic signals powered by radioactive heating from unstable nuclei synthesized in the rapid-neutron-capture process (so-called r-process) are particularly interesting. Such signals could be the first direct detection of freshly synthesized r-process elements. This phenomenon is called a "kilonova" or "macronova." Indeed, the afterglow of GRB 130603B exhibited a near-infrared excess that may be evidence of heating and increased opacity from the presence of newly synthesized heavy elements [2, 3, 4].

Accurate numerical simulations of the r-process are necessary to reliably predict the radioactive heating of CBMs. Previous studies of neutron star mergers have indicated that the nuclear fission of neutron-rich nuclei is crucial to determining resulting nuclear abundances after the r-process [5, 6]. In this paper, we report on r-process nucleosynthesis simulations [7] of binary neutron star mergers based upon a new nuclear reaction network code. We have added new nuclear data for nuclear masses, nuclear fission probabilities, fission distributions, etc. These new data play a crucial role in the r-process.

2. R-Process Calculation

2.1 Nuclear Input

Our reaction network code is described in [8]. This code has been updated with a new nuclear mass model [9], along with new beta-decay rates, beta-delayed neutron emission probabilities, beta-delayed fission probabilities, fission fragment distributions [10, 11], and alpha-decay rates [12]. As summarized in [7, 10], this model predicts that nuclei become unstable to fission in a region of higher nuclear masses than other nuclear models. This feature is crucial to the termination point of the r-process path as discussed below.

2.2 Fluid Data

In our nucleosynthesis calculations, we make use of the hydrodynamic simulations of binary neutron star merger of Refs. [6, 13, 14]. They calculated various combinations of the binary neutron-star mass ratio. We chose their 1.0-1.0 $M_{\odot}$ binary neutron star merger simulation. We note, however, that this choice of masses does not affect the resulting nuclear abundances [6]. Their simulations were based upon Newtonian smoothed particle hydrodynamics [15]. The equation of state of [16, 17] was utilized and neutrino transport was calculated using the neutrino leakage scheme [18].

Their simulation ends after about 15 ms. We then extrapolated the density and temperature to later times by assuming an adiabatic free expansion. Nuclear heating must be taken into account in this extrapolation because many nuclei are unstable and their radioactive decay generates enough heat to change the temperature [6]. A heating efficiency parameter ε_{th} was introduced to take into account the energy loss by escaping neutrinos generated in nuclear reactions and decay. For simplicity, in our calculations we take this to be unity. The dependence of the resulting abundances on ε_{th} was discussed in [6].

2.3 Final Elemental Abundances

The blue dashed line in Figure 1 shows isotopic abundances from our simulation of a 1.0-1.0 $M_\odot$ binary neutron star merger. There are several features worthy of note in this abundance pattern. The first feature is the disappearance of the second (A$\sim$130) r-process peak. This is because the extremely high neutron number density causes all seed nuclei to be transformed into nuclei with masses heavier than the second r-process peak. Also, the second r-process peak and the rare-earth (RE) nuclei are formed by nuclear fission after the neutron capture reactions cease. This indicates that these abundances are highly sensitive to the nuclear fission mass distributions. The second feature is that the abundances of the RE nuclei are as high as the abundances of the third r-process peak. This is because our nuclear mass model predicts that fissile nuclei begin at heavier nuclear masses than other theoretical models [10]. This causes more nuclei to undergo nuclear fission after the cessation of the neutron capture reactions.

3. Reproduction of the Solar R-Process Elements

The obtained elemental abundances from neutron star mergers are quite different from those of the solar r-process abundances [19]. One possible interpretation of this is that binary neutron star mergers do not contribute to the production of the solar r-process elements at all. Here, however, we propose [7] another possible interpretation: neutron star mergers produce only a part of the solar r-process elements. In order to confirm this hypothesis, we have summed the elemental abundances of three candidates for the r-process, i.e. neutron star mergers, magnetorotational supernovae, and the neutrino driven wind in CCSNe. We then match these sums to the solar r-process abundances. To do this we have utilized isotopic abundances from [20] as typical of the neutrino driven wind, and abundances from [21] as typical of magnetorotational supernovae. Weight factors for the neutron star merger and the neutrino driven wind relative to the magnetorotational supernova are introduced to match the solar r-process abundances. These parameters were determined [7] by a χ^2 minimization to the solar r-process abundances. The solar r-process abundances are normalized to fit the resulting sum of the three r-process components at $A = 153$.

The best fit values for the neutron star merger and the neutrino driven wind are 0.09 and 4, respectively. The red solid line in Figure 1 shows the best fit curve of the sum of the three r-process components. In this scenario, neutron star mergers contribute significantly to the production of the elemental abundances of the REH, and also to the abundances above and below the r-process peaks. The total elemental abundances agree well with the solar r-process abundances. The weight factors inferred here [7] are consistent with independent estimates of the weight factors. These can be evaluated by galactic event rates times ejected r-process masses for neutron star mergers and the neutrino driven wind relative to magneto-rotational supernovae, respectively. Here we refer

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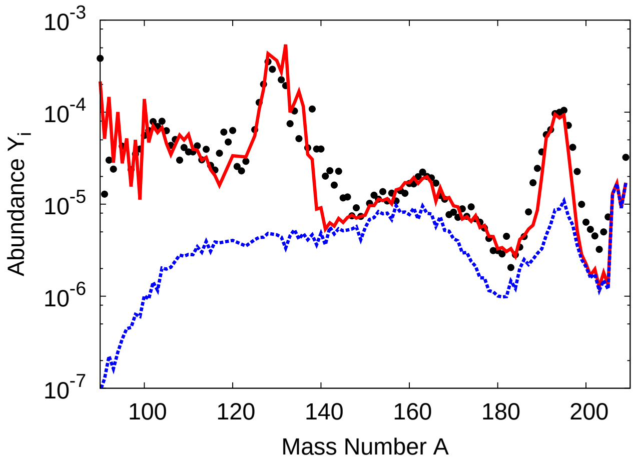

Figure 1: Final abundance pattern from neutron star mergers (blue dashed line) compared with the r-process abundances in the solar system (black dots) [19]. The red solid line represents the sum of the inferred abundances from neutron star merger, the neutrino driven wind and magnetorotational supernovae. The weight factors were determined by a χ^2 minimization to match the solar r-process abundances.

to [6, 20, 22, 23, 24, 25], as evidence that our fit values are consistent with the independently estimated values.

4. Summary and Perspective

We have carried out r-process nucleosynthesis calculations within neutron star mergers using a new nuclear network code [7]. Our simulations exhibit a very flat abundance pattern due to our new theoretical fission probabilities and fission fragment distributions. This study suggests that the solar r-process elements are formed by superposition of neutron star mergers, neutrino driven winds and magneto-rotational supernovae. The inferred ejected masses and galactic event rates are consistent with this assumption.

In future studies our scenario could be constrained by reducing uncertainties of each event rate and the ejected masses. Also, detections in forthcoming GW observatories may improve the estimated event rate for neutron star mergers. Advances in the numerical simulations of stellar evolution, supernovae and neutron star mergers may also provide future constraints on this interpretation of the r-process.

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