

The r -Process in Black Hole Winds

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Abstract. All the current r -process scenarios relevant to core-collapse supernovae are facing severe difficulties. In particular, recent core-collapse simulations with neutrino transport show no sign of a neutron-rich wind from the proto-neutron star. In this paper, we discuss nucleosynthesis of the r -process in an alternative astrophysical site, “black hole winds”, which are the neutrino-driven outflow from the accretion torus around a black hole. This condition is assumed to be realized in double neutron star mergers, neutron star – black hole mergers, or hypernovae.

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INTRODUCTION

In the past decades, core-collapse supernovae have been considered to be the most promising astrophysical site that provides the suitable conditions for nucleosynthesis of the r -process. The scenarios include the neutrino-driven wind [1, 2, 3, 4, 5, 6], the prompt explosion of a collapsing iron core [7] or of an oxygen-neon-magnesium (O-Ne-Mg) core [8], and the shocked surface layer of an O-Ne-Mg core [9]. However, recent hydrodynamical simulations of collapsing iron cores (e.g., [10]) and of an collapsing O-Ne-Mg core do not support the prompt explosion [11] or the shocked surface layer [12] scenarios. The nucleosynthesis calculations [13, 14] with these hydrodynamical results also show that the production of neutron-capture elements proceeds only up to $A = 90$ ($N = 50$). Furthermore, recent long-term simulations of core-collapse supernovae show that the neutrino-driven outflows are proton-rich all the way [15, 16], which poses a severe difficulty to all the scenarios relevant to the neutrino-driven winds of core-collapse supernovae.

In contrast, another popular scenario of the astrophysical r -process, the mergers of double neutron stars (NS-NS) [17] or of a black hole and a neutron star (BH-NS) [18] in a close binary system has not been fully explored. The decomposition of cold unshocked neutron-rich matter from NS-NS is suggested to be an alternative or additional r -process site [19, 20, 21, 22]. In addition, both NS-NS and BH-NS are expected to form an accretion torus around a black hole, giving rise to the neutrino-driven winds (“black hole winds”), which are also expected to provide suitable physical conditions for the r -process [23].

The reason that the merger scenarios have been disfavored compared to those of core-collapse supernovae is probably due to discrepancies between Galactic chemical evolution models and the spectroscopic analyses of Galactic halo stars. The estimated low event rate ($\sim 10^{-5} \text{ yr}^{-1}$) of mergers and the long lifetime of the binary system

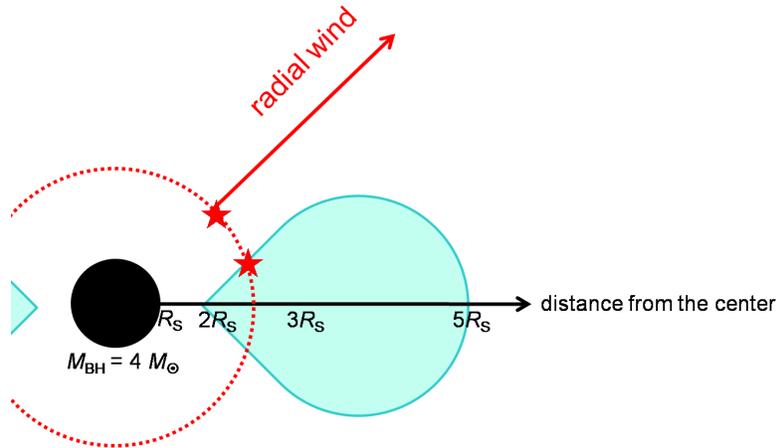


FIGURE 1. Sketch of our model settings for the black hole winds. A rotating black hole with the mass $M_{\text{BH}} = 4M_{\odot}$ is located in the center of an accretion torus (“neutrino surface”) that lies between $2R_{\text{S}}$ and $5R_{\text{S}}$ from the center, where R_{S} is the Schwarzschild radius ($= 11.8 \text{ km}$). The wind is assumed to be radial, where the neutrino surface is replaced with an equivalent radius from the center (e.g., the star on the dotted circle).

(> 100 Myr) are expected to lead to the delayed appearance of the r -process elements in the Galactic history with too large star-to-star scattering of their abundances [24], which is in conflict with the observational results of halo stars. However, some recent studies of Galactic chemical evolution based on the hierarchical clustering of sub-halos [25, 26] do not exclude the mergers as the dominant astrophysical site of the r -process. Therefore, the mergers cannot be excluded as the r -process site, and more studies of nucleosynthesis are desired when considering the difficult situation of the supernova scenarios.

In this paper, we examine the r -process in black hole winds, which are common both in NS-NS and BH-NS mergers, and presumably, in “collapsars” [27, 28]. The previous studies of nucleosynthesis relevant to these conditions are based on phenomenological models [28, 23]. Currently, however, three-dimensional simulations of the mergers are out of reach for the wind phase after the formation of a stable accretion torus [17, 18]. Hence, we apply the semi-analytic wind model for nucleosynthesis calculations, which has been developed for the studies of the r -process in the neutrino-driven winds of core-collapse supernovae [5, 29].

MODELING THE BLACK HOLE WINDS

Our model of black hole winds is based on the semi-analytic, spherically symmetric, general relativistic model of proto-neutron star winds [5, 29], as illustrated in Figure 1. The mass of a central black hole is taken to be $M_{\text{BH}} = 4M_{\odot}$, which may correspond to, e.g., NS-NS binaries with the equal masses of $\sim 2M_{\odot}$ or BH-NS binaries with the masses of $\sim 2.5M_{\odot}$ and $\sim 1.5M_{\odot}$. This can be also interpreted as the accreting black hole of the collapsar from a massive (> $30M_{\odot}$) progenitor. The accretion torus around

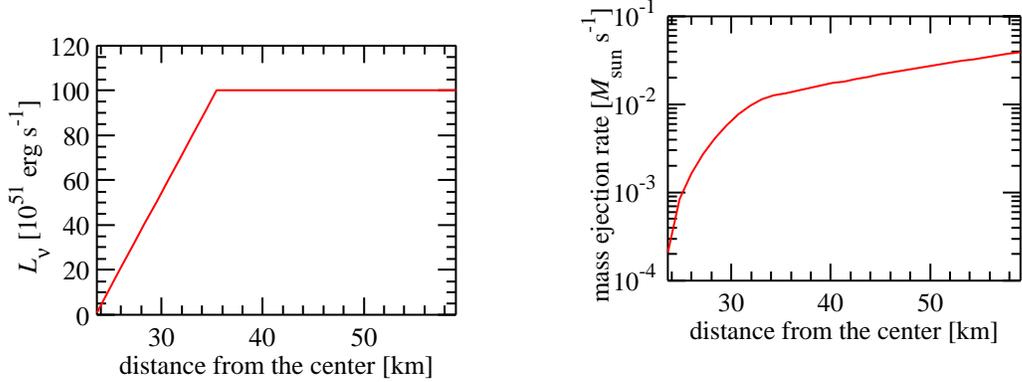


FIGURE 2. Left: Neutrino luminosity L_ν as a function of the distance from the center. L_ν is assumed to increase linearly from 10^{51} erg s $^{-1}$ to 10^{53} erg s $^{-1}$ between $2R_S$ ($= 23.6$ km) and $3R_S$ ($= 35.4$ km) and take a constant value on the outer side. Right: Mass ejection rate \dot{M} obtained with the L_ν profile assumed in the left panel, as a function of the distance from the center.

the black hole, which is defined as the “neutrino surface”, is assumed to lie between $2R_S$ ($= 23.6$ km) and $5R_S$ ($= 59.0$ km) from the center (where R_S is the Schwarzschild radius $= 11.8$ km) in the light of detailed hydrodynamical simulations of BH-NS merging [18].

In order to connect the aspherical configuration of the winds from the torus to our spherical model, an arbitrary point on the torus is replaced by a point on the hypothetical neutrino sphere with an equal distance from the center, R_ν (dotted circle in Figure 1). The solution of the wind from the neutrino sphere with M_{BH} and R_ν is then obtained in the same manner as for proto-neutron star winds. The rms average neutrino energies are taken to be 15, 20, and 30 MeV, for electron, anti-electron, and the other flavors of neutrinos, respectively [18]. The neutrino luminosities of all the flavors are assumed to be the same value L_ν . The mass ejection rate at the neutrino sphere \dot{M} is determined so that the wind becomes supersonic through the sonic point.

As anticipated from Figure 1, the neutrino flux from the outer regions of the torus is shielded in the vicinity of the black hole by the presence of the torus itself. In order to mimic this effect in our spherical models, we simply assume that L_ν increases linearly from 10^{51} erg s $^{-1}$ to 10^{53} erg s $^{-1}$ between $2R_S$ ($= 23.6$ km) and $3R_S$ ($= 35.4$ km) and takes a constant value on the outer side, as shown in Figure 2 (left panel). This roughly reproduces the peak energy deposition rate by $\nu\bar{\nu}$ annihilation into e^+e^- pairs in the vicinity of the black hole ($\sim 10^{30}$ erg s $^{-1}$ cm $^{-3}$) [17, 18]. We define the outflows from $R_\nu < 3R_S$ and $R_\nu > 3R_S$ as the inner and outer winds, respectively.

As shown in Figure 2 (right panel), inner winds have rather small \dot{M} owing to the small L_ν at R_ν . As a result, the inner winds obtain substantially higher asymptotic entropies (at 0.5 MeV, up to $\sim 800k_B$ per nucleon, where k_B is the Boltzmann constant; Figure 3, left panel) and short expansion timescales (defined as the e -folding time of temperature from 0.5 MeV, down to ~ 1 ms; Figure 3, right panel). This is due to the larger heating rate

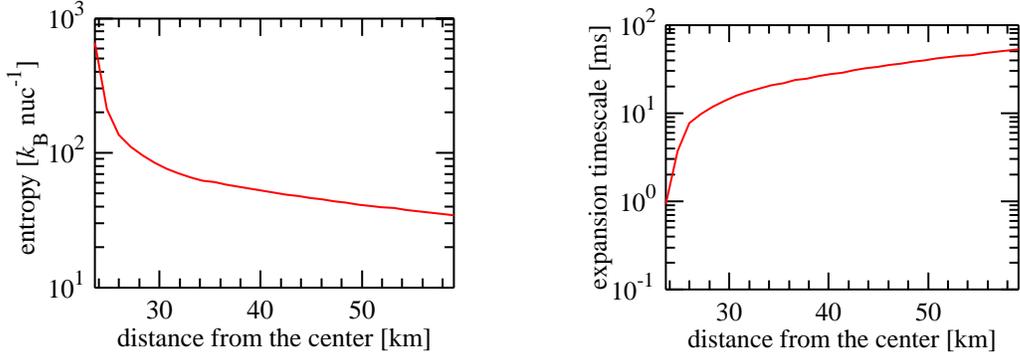


FIGURE 3. Left: Asymptotic entropy (at 0.5 MeV) as a function of the distance from the center. Right: Expansion timescale (the e -folding time of temperature from 0.5 MeV) as a function of the distance from the center.

per unit mass by $\nu\bar{\nu}$ annihilation *after* leaving the neutrino surface, owing to the smaller matter density in the inner wind (see the same effect in anisotropic proto-neutron star winds in [29]). This indicates that the inner winds are favored for the strong r -process (see speculations in [17]).

NUCLEOSYNTHESIS IN WINDS

The nucleosynthetic yields in each wind trajectory are obtained by solving an extensive nuclear reaction network code. The network consists of 6300 species between the proton and neutron drip lines, all the way from single neutrons and protons up to the $Z = 110$ isotopes (see [14] for more detail). Each nucleosynthesis calculation is initiated when the temperature decreases to 9×10^9 K, at which only free nucleons exist. The initial compositions are then given by the initial electron fraction Y_{e0} (number of protons per nucleon). In this study, Y_{e0} is taken to be a free parameter. We explore the nucleosynthesis for all the winds with $Y_{e0} = 0.10, 0.15, 0.20, 0.25, 0.30$, which are consistent with a recent hydrodynamic study of BH-NS [23]. Note that the initial Y_e in the torus, consisting of decompressed NS matter is low, and Y_e in the outgoing wind remains to be low because $L_{\bar{\nu}_e} > L_{\nu_e}$ for the torus during a significant time of its evolution (e.g., [30]).

The neutron-to-seed ratios at the onset of r -processing (defined at 2.5×10^9 K) are shown in Figure 4 (left panel). Note that Y_e at this stage is ~ 0.1 higher than Y_{e0} owing to the neutrino effects, which is obviously overestimated in our assumption of $L_{\bar{\nu}_e} = L_{\nu_e}$. In all the Y_{e0} cases, the neutron-to-seed ratios are substantially higher than 100 (that is required for the 3rd r -process peak formation) in the innermost winds owing to the high entropies and the short expansion timescales (Figure 3), where the fission cycling is expected. In the outer winds, however, only the low Y_{e0} case attains a high neutron-to-seed ratio (up to ~ 70) because of the moderate entropies and expansion timescales.

For each Y_{e0} case, the nucleosynthetic yields are mass-averaged over the entire range

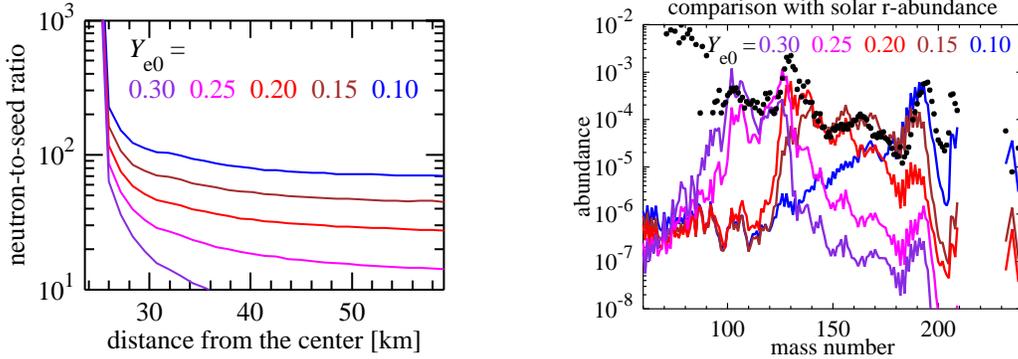


FIGURE 4. Left: Neutron-to-seed ratios at the onset of r -processing (2.5×10^9 K) as a function of the distance from the center for various initial electron fractions ($Y_{e0} = 0.10, 0.15, 0.20, 0.25,$ and 0.30). Right: Mass-averaged nucleosynthetic yields for various initial electron fractions (lines), which are compared with the solar r -process distribution (dots).

of R_v (from $2R_S$ to $5R_S$), which is shown in Figure 4 (right panel). Despite the high neutron-to-seed ratios in the inner winds, the $Y_{e0} = 0.25$ and 0.30 cases contribute only up to the 2nd r -process peak ($A = 130$) because of the very small \dot{M} in the inner winds (Figure 2, right panel). Our result indicates that neutron-rich winds with $Y_{e0} < 0.20$ (< 0.30 at the onset of r -processing) are required to account for the 3rd r -process peak formation ($A = 195$). Notable is that the “envelope” made by the curves for various Y_{e0} reasonably fits the solar r -process distribution. This implies that the wide range of Y_e (in terms of space and time) in the presented case leads to production of all the heavy r -process nuclei.

IMPLICATIONS

Our model of black hole winds suggests that the innermost wind trajectories attain substantially higher entropies ($> 100k_B$ per nucleon) and shorter expansion timescales (< 10 ms). This indicates that all the relevant astrophysical conditions, i.e., NS-NS and BH-NS mergers and collapsars (or hypernovae) are potential factories of the r -process nuclei. However, our nucleosynthesis result shows that significant neutron-richness in the wind is still required in order to account for the formation of the 3rd r -process peak. In this regard, NS-NS and BH-NS are favored compared to collapsars, since the accretion tori originate from neutron-star matter (and moreover, $L_{\bar{\nu}_e} > L_{\nu_e}$) in the former case and iron-peak (or alpha) elements in the latter, respectively.

Obviously, more elaborate hydrodynamical studies of the relevant astrophysical sites are needed to obtain information of the neutrino field that controls the dynamics as well as the neutron-richness in the black hole winds. Note that the aforementioned astrophysical phenomena are also suggested to be the sources of (short and long, respectively) gamma-ray bursts. An interesting possibility in this context is that the neutron-rich nu-

clei ejected in and after NS-NS or BH-NS mergers might lead to detectable transient electromagnetic signal [31]. The studies of Galactic chemical evolution will be also important to test the contributions of NS-NS, BH-NS, and collapsars (or hypernovae) to the enrichment history of the r -process elements in the Milky Way.

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