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Heavy element synthesis in neutrino-processed black hole accretion disk ejecta

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Astrophysical systems that include a stellar-mass black hole surrounded by a rapidly accreting disk are potentially key contributors to galactic nucleosynthesis. Such systems can form during the merger of two compact objects, such as two neutron stars or a neutron star and a black hole, or during the core collapse of a massive, rotating star. Some of the mass ejected from these systems is expected to be processed in the accretion disk; any material from the inner regions of the disk will also be influenced by the disk neutrino emission as it streams outwards. Thus a careful accounting of the neutrino physics is required to accurately predict nucleosynthetic outcomes. Here we discuss how GR effects on the neutrino spectra and neutrino oscillations can impact the resulting nucleosynthesis.

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1. Introduction

A black hole accretion disk (AD-BH) can result from the collapse of a massive, rotating star ('collapsar') or the collision of two compact objects in a binary system. In either scenario, a stellar-mass black hole is created that is fed by a rapidly accreting torus of debris, originating from the stellar envelope in the former case or the tidally-disrupted neutron star in the latter. The rapid accretion, with rates estimated from fractions to several solar masses per second, can potentially power a gamma-ray burst (GRB) [1, 2, 3, 4, 5, 6, 7, 8]. With or without the accompanying GRB, these systems include multiple environments conducive to element synthesis.

During the merger of two neutron stars or a neutron star and a black hole in a binary system, mass can be ejected promptly, in the tidal tails, and in outflows from the resulting AD-BH. The prompt ejecta as well as that stripped from the tidal tails is essentially unprocessed neutron star material [9, 10]. This material is expected to undergo vigorous rapid neutron capture, or *r*-process, nucleosynthesis with fission recycling, producing some fractions of a solar mass of radioactive species that can lead to an observable electromagnetic counterpart [11, 12, 13] and contributing to the galactic inventory of elements heavier than iron [14, 15, 16]. The remaining mass ejected from the merger event will be processed in the accretion disk [17, 18, 19, 20], where it will be heated, dissociated (perhaps completely) into nucleons, and composition shaped by the weak interactions:

$$p + e^- \rightleftharpoons \nu_e + n \tag{1.1}$$

$$n + e^+ \rightleftharpoons \bar{\nu}_e + p. \tag{1.2}$$

The accretion disk is extremely hot and dense and a copious emitter of neutrinos. Thus, the forward and reverse reactions above will determine the composition of not only the disk itself but the outflows from the disk [21, 22, 23]. About half of the disk is expected to be expelled in some combination of viscous, e.g. [24], and/or neutrino-driven, e.g. [25], outflows, with the nucleosynthetic outcome determined by hydrodynamics of the outflow and the weak interaction physics [22, 23, 26, 27].

During a collapsar event, nucleosynthesis can occur in the stellar envelope and in the jet, e.g., [28, 29, 30, 31]. This explosive nucleosynthesis can produce Nickel-56, which drives the supernova light curve associated with long-duration GRBs. The early baryon-poor jet might produce some interesting light nuclei [32], and at late times may even drive an unusual *r* process [33, 34]. In addition, an AD-BH will be produced that can contribute to the nucleosynthetic outcome [35, 18, 19]. This AD-BH and its outflows are similar to the merger case described above, except here the disk is expected to last longer and accrete more slowly, as it is fed by the extended stellar envelope. It also starts from proton-rich material, as opposed to the neutron-rich neutron star material in the merger case; thus the collapsar disk is deleptonizing as it evolves while the merger disk is leptonizing.

In this short review, we will focus on the element synthesis in the neutrino-processed outflows from AD-BHs in each of these potential astrophysical scenarios. In particular, we will examine the importance of two key pieces of neutrino physics on the composition of the ejected material: general relativistic effects on the neutrino spectra and neutrino oscillations.

2. GR effects on the neutrino spectra

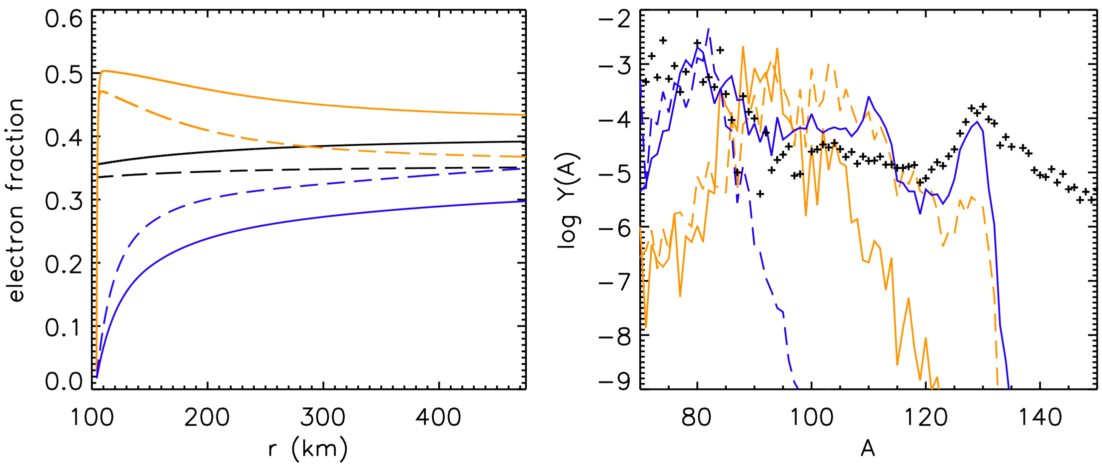

Figure 1: The left panel shows electron fractions (colored lines) and neutrino-only equilibrium electron fractions (black lines) for two spherical wind trajectories from the merger disk from [26]. The trajectories are characterized by an entropy per baryon $s/k = 20$ and a timescale of $\tau = 5$ ms (blue lines) or with $s/k = 75$ and $\tau = 75$ ms (orange lines). The neutrinos are treated as Newtonian in the calculations indicated by the dashed lines, while the solid lines show the results when general relativistic neutrino redshift and trajectory bending are taken into account [38]. The right panel shows the final nuclear abundances in each case, with the crosses indicating the scaled solar r-process residuals [36].

The AD-BH produced in a merger event is very rapidly accreting, with accretion rates estimated to be $\sim 0.1 - 10$ solar masses per second. The extremely hot and dense inner regions cool primarily by neutrino emission, which can be modeled as thermal emission from neutrino and antineutrino decoupling surfaces. The decoupling surfaces are analogous to the protoneutron star neutrinosurfaces in regular core-collapse supernovae, but have a donut-like shape due to the disk geometry. Examples of merger AD-BH neutrino decoupling surfaces can be found in, e.g., [22, 26, 23]. Due to the neutron-richness of the disk, the antineutrinos decouple from deeper within the disk, and as a result their emission is hotter than the electron neutrinos and comes from a smaller area [26, 37]. Since the disk is leptonizing, the overall number flux of electron antineutrinos exceeds the electron neutrinos.

The hotter and more numerous antineutrinos are expected to drive any neutrino-processed outflows neutron rich, via the reverse weak interactions above. Early studies showed that this could result in a weak or main r process occurring in the outflows [22, 26, 23, 27]. In [22, 26] the most robust production of r-process nuclei was found to be in outflows that were either (1) low entropy, fast expansion, such that the neutron-richness of the disk is retained, or (2) high entropy, slow expansion, such that the electron fraction in the outflow is reset by the neutrino interactions.

While the entire disk emits neutrinos, most of the emission comes from the innermost regions, close to the last stable orbit of the black hole. Thus, the neutrinos emitted from that region will be subject to general relativistic effects, such as redshifting of the neutrino energies and bending of the neutrino trajectories [37]. These can have important impacts on the outflow nucleosynthesis [38, 39].

As described in [38], with the general relativistic effects included, case (1) described above becomes more robust, as the energy redshift reduces the high energy tail of the neutrino fluxes. The neutrino interaction rates are therefore less than in the Newtonian case, and, for fast, low entropy flows, more of the neutron richness of the disk is retained. This is shown in Fig. 1, where the blue lines indicate the results of a low entropy, fast outflow trajectory from the merger disk of [26]. Without general relativistic effects on the neutrino spectra, the outflow electron fraction approaches the neutrino-only equilibrium value of 0.35 and $A \sim 80$ peak nuclei are formed. With the redshifted energies and trajectory bending taken into account, the neutrinos do not completely reequilibrate the electron fraction, and the electron fraction remains low enough to result in the production of the second r-process peak.

However, in case (2), general relativistic effects act in the opposite direction [38]. Since the antineutrinos are primarily emitted closer to the black hole than the neutrinos, the general relativistic effects tend to reduce the antineutrino flux more than the neutrino flux. This pushes up the equilibrium electron fraction to the point where the production of r-process nuclei is reduced or eliminated. The former is illustrated in Fig. 1, with the orange lines that show the results of a higher entropy, slower outflow trajectory for the same merger disk. In this example, nuclei up to the second r-process peak are predicted to form with a Newtonian treatment of the neutrinos, but when the GR effects are included mostly $A \sim 90$ nuclei are made.

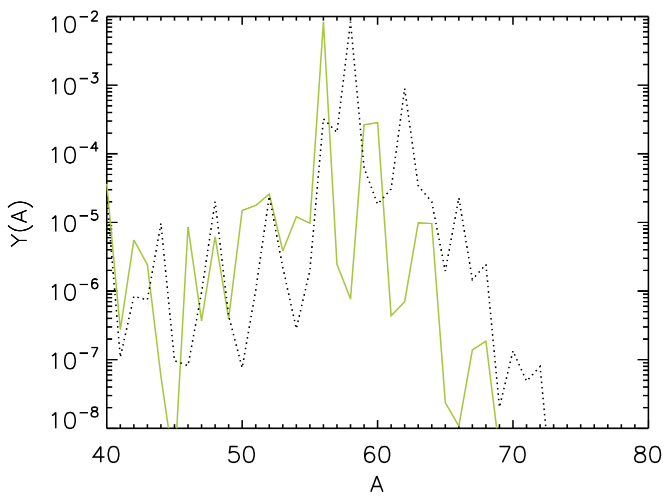

Figure 2: Abundances $Y(A)$ as a function of mass number A for an example trajectory from [39] with entropy $s/k = 20$ and timescale $\tau = 10$ ms, with (green solid line) and without (black dotted line) general relativistic effects on the neutrino spectra.

Another example of this latter effect is considered in a separate merger disk model in [39]. For this disk [24] the neutrino-only equilibrium electron fraction is predicted to be just below 0.5, without GR effects. Including GR effects on the neutrino spectra can shift this to just above 0.5. An example of the resulting element synthesis is shown in Fig. 2; when GR effects are included, production shifts from Nickel-58 to Nickel-56. For most of the outflow parameter space considered in [39], the neutrino-processed outflows from this disk primarily yielded Nickel-56.

3. Neutrino oscillation effects

Another aspect of neutrino physics that can impact AD-BH nucleosynthesis is neutrino flavor transformation. In addition to the standard vacuum and matter-enhanced MSW oscillations,

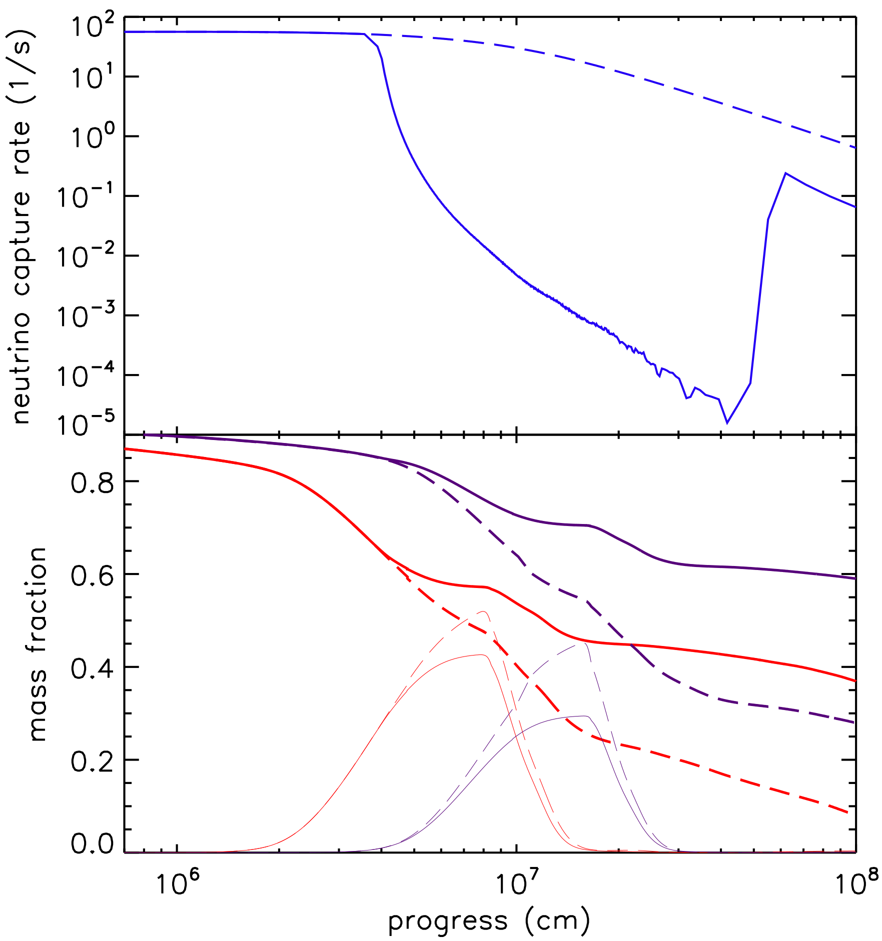

Figure 3: The top panel shows the neutrino capture rate on neutrons as a function of progress along a radial matter trajectory for cases with (solid blue) and without (dashed blue) neutrino oscillation effects. The bottom panel shows the resulting mass fractions of neutrons (thick lines) and alpha particles (thin lines) along the radial trajectory for outflow parameters $s/k = 20$ and $\beta = 1.4$ (red) or $\beta = 0.2$ (purple), again with (solid) and without (dashed) neutrino oscillation effects.

neutrino-neutrino self-interactions can also drive flavor transformations in environments with intense neutrino emission. The latter has been considered carefully in the context of a regular core-collapse supernova, see e.g. [40] for a review. There, flavor transformations between the cooler electron neutrinos and hotter μ and τ neutrinos result in enhanced neutrino interaction rates, which can potentially boost a νp process [41] or hinder an r process [42] in a supernova neutrino-driven wind.

In a collapsar AD-BH, a similar transformation could occur, though the impact on the nucleosynthesis will be quite different [43]. Collapsar AD-BH emit primarily electron flavor neutrinos, in contrast to a regular supernova that emits all flavors roughly equally. Thus, electron neutrinos and antineutrinos can transform to μ/τ flavors, but there is too little μ/τ emission for the reverse transformation to play a significant role. Thus, unlike the supernova case, a flavor transformation can result in drastically *lower* charged-current neutrino interaction rates.

In addition the disk geometry may lead to another type of flavor transformation. Overall, the collapsar AD-BH is expected to be deleptonizing, so that the neutrino number fluxes outweigh the antineutrino fluxes overall. However, in the inner regions of the disk, at points close to the neutrino decoupling surfaces, a matter element will see primarily the hotter antineutrinos. So along an outflow trajectory from the inner AD-BH, antineutrinos dominate at first while neutrinos dominate farther out. This results in a change in the sign of the neutrino self-interaction potential, which can drive a unique type of flavor transformation not possible in a regular supernova [43].

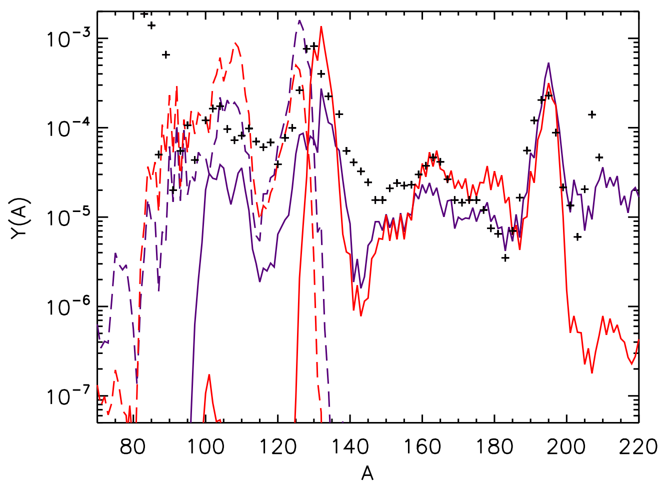

Figure 4: Final abundance patterns $Y(A)$ versus mass number A for the two cases shown in the lower panel of Fig. 3, with (solid lines) and without (dashed lines) oscillation effects. As shown in Fig. 3, the main oscillation effect occurs prior to the formation of alpha particles in the trajectory with the faster acceleration (purple lines), leading to an *r*-process with fission cycling.

An example of the potential net result of these two effects is shown in Figs. 3 and 4. For this initial study we started with a collapsar-type AD-BH disk model [20], calculated the neutrino decoupling surfaces as in [19], and then approximated the neutrino emitting surfaces as constant temperature flat disks. We calculated the neutrino flavor transformations along radial trajectories, including the effects of neutrino self-interactions in the single-angle approximation [43]. The top panel of Fig. 3 shows the resulting neutrino interaction rate along the trajectory, both with and without oscillation effects. A strong flavor transformation occurs sufficiently close to the disk that we can expect it to modify the predicted element synthesis. To estimate these effects, we ran the nucleosynthesis with a parameterized outflow model from [22]. The bottom panel of Fig. 3 shows the evolution of the mass fractions of neutrons and alpha particles in the outflow for two example trajectories, using the neutrino interaction rates from the top panel. Without neutrino interactions, both cases experience a strong α effect [44]—once all of the protons are bound into αs, neutrino interactions continue to transform neutrons into protons, and the newly-created protons immediately bind into more αs. The α effect increases the number of seed nuclei and decreases the available free neutrons for capture, and so promising neutron-rich conditions end up producing only up to the second *r*-process peak; final nucleosynthesis results are shown in Fig. 4. With oscillations included, however, neutrino interactions are effectively shut off either during or before α formation, depending on the outflow conditions. Thus, many fewer αs form and more free neutrons remain, such that a vigorous main *r*-process results in both cases.

4. Conclusion

Astrophysical events that form stellar mass black holes surrounded by accretion disks—compact object mergers and collapsars—can be important contributors to galactic nucleosynthesis. The bulk of the nucleosynthetic output is likely to be from the prompt ejecta/tidal tails in the merger case and explosive nucleosynthesis in the collapsar. However, neutrino-processed outflows from the AD-BH can also play an important role, particularly if rare nuclei are produced, like the *r* process, or if a significant amount of Nickel is synthesized.

Here we have reviewed some recent work on the impact of two aspects of neutrino physics on AD-BH outflow nucleosynthesis: general relativistic effects on the neutrino spectra [38, 39] and neutrino oscillations [43]. In our study of the former, we have found that GR effects such as neutrino energy redshifts and neutrino trajectory bending do indeed shape the resulting element synthesis, but exactly how is highly dependent on the disk and outflow model chosen. Neutrino oscillations from AD-BH have only just begun to be considered, and in this early work we have shown how a novel type of flavor transformation could result in a collapsar *r* process. Additional studies are needed to carefully examine these effects, which ultimately should be combined in a self-consistent disk and outflow calculation.

Acknowledgements

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