PROCEEDINGS OF SCIENCE

Element production in the Outflow from Black Hole Accretion Disks

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Gamma-ray bursts, while rare, may be important contributors to galactic nucleosynthesis. Here we consider the types of nucleosynthesis that can occur as material is ejected from a gamma-ray burst accretion disk. We calculate the composition of material within the disk as it dissociates into protons and neutrons and then use a parameterized outflow model to follow nuclear recombination in the wind. From the resulting nucleosynthesis we delineate the disk and outflow conditions in which iron peak, *r*-process, or light *p*-process nuclei may form. In all cases the neutrinos have an important impact on the final abundance distributions.

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1. Introduction

The outflow from accretion disks surrounding black holes is a relatively new environment in which to consider nucleosynthesis [1, 2, 3]. This environment has received attention lately because accretion disks around black holes have been suggested as the mechanism which powers gamma ray bursts, e.g. the collapsar model [4]. In this model a massive star which undergoes core collapse forms an accretion disk around a black hole instead of the canonical proto-neutron star. This geometry is a good one for producing a jet, the energy for which may come from neutrino - antineutrino annihilation or be extracted electromagnetically from a rotating black hole.

Aside from the ultrarelativistic jet which forms along the rotation axis of the black hole, there will be additional outflow from the accretion disk; Fig. 1 shows a schematic view. Estimates show that up to half of the disk material will be ejected from the disk [5]. The disks are sufficiently hot, $\sim$ 6 MeV, that the material in the disk is composed of free nucleons. In the outflow, this material expands, cools and undergoes a primary nucleosynthesis process.

Neutrinos are emitted from these disks in great numbers. As they exit the disk, they interact with the outflowing material through the reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$. These reactions influence the neutron-to-proton ratio and therefore the nucleosynthesis [6].

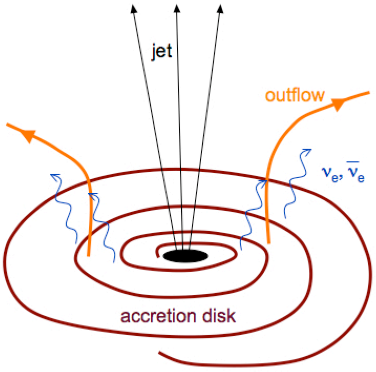

Figure 1: Schematic drawing of the accretion disk environment. The disk might form a jet in the center. In this contribution we study the nucleosynthesis in the outflow.

2. Calculations

The collapsar model predicts disks with accretion rates of about 0.1 $M_\odot$/s [4]. Calculations of the electron fraction in steady-state models of these disks [1] show that the material becomes quite neutron rich $Y_e = 1/(n/p+1) \approx 0.1$ at some points, although if the neutrinos are trapped the electron fraction rises considerably. As the material flows away from the disk, the electron degeneracy which kept the neutron-to-proton ratio low is lifted and electron and positron capture reset Y_e to much higher values. The resulting nucleosynthesis is determined primarily by the electron fraction.

Here we calculate the nucleosynthesis starting with disk Y_es calculated from the steady state disk models of [7, 8] and following first the evolution of Y_e [6] and then nuclear recombination [9] in the outflow parameterized as described in [6]. The key parameters of the outflow are the entropy per baryon s/k and β, an adjustable parameter that controls the acceleration of the flow, with low β corresponding to rapid acceleration. Neutrino interactions become particularly important in trajectories with large β, as slowly accelerating flows are exposed to a higher neutrino fluence.

In Fig. 2 we show the values of the outflow Y_e overlaid on a plot of the mass fraction of ^{56}Ni in our parameter space. It is only at around $Y_e = 0.5$ that the ^{56}Ni begins to form. Entropy also influences the nucleosynthesis beyond its role setting the Y_e; in the higher entropy trajectories the triple-α reaction can freeze out before the α-particles fully assemble into iron peak nuclei [9].

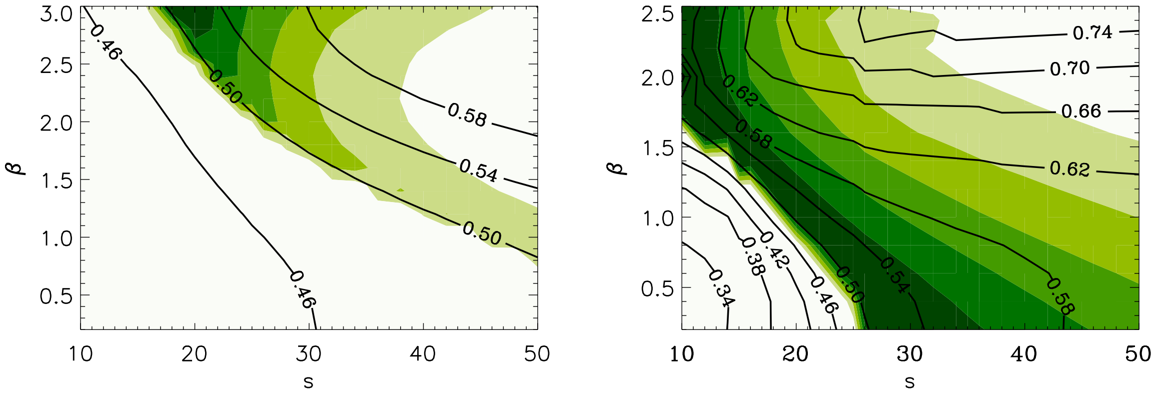

Figure 2: Shows the mass fraction of ^{56}Ni as a function of outflow parameter β and entropy per baryon s/k for a disk with accretion rate 0.1 $M_\odot$/s (left) and 1.0 $M_\odot$/s. Dark shaded regions are shown in order from darkest to lightest for mass fractions of 0.5, 0.4, 0.3, 0.2, and 0.1. Contours of constant Y_e are overlaid on the plot.

There are a number of interesting intermediate-mass nuclei, such as ^{42}Ca, ^{45}Sc, ^{49}Ti, and ^{64}Zn, that have large overproduction factors in these outflows as first discussed in Pruet et al. [10]. Here we examine Zinc. According the the surveys in [11], Zinc does not track well elements that are produced primarily in core collapse supernovae, such as Magnesium, suggesting an alternate production mechanism for Zinc. In fact the ratios [Zn/Fe] and [Zn/Mg] increase with decreasing metallicity, indicating relatively larger production early in the evolution of the Galaxy, as may be consistent with more massive stars.

Zinc is very significantly overproduced in these outflows, as seen in Fig. 3. The largest overproduction factors for Zinc occur for electron fractions at just slightly less than one half. This is similar to the alpha rich freeze-out of the neutrino driven wind of the supernova [12, 13], but the overproductions we observe are larger. Overproduction factors greater than 10 occur for conditions that are just slightly proton rich, similar to what is observed in the hot bubble of the supernova [14, 15]. The band of overproduction along the top of the plot, where the outflow is slow, shows enhancement due to neutrino capture on nucleons.

An r-process can be obtained if the disks are sufficiently rapidly accreting [16]. The left panel of Fig. 4 shows final scaled abundances versus mass number for sample trajectories from a disk with accretion rate 10 $M_\odot$/s compared to the solar r-process abundances. The production of r-process nuclei is possible over a broad range of the parameter space, as seen in the right panel of Fig. 4. Low entropy trajectories retain the neutron richness of the disk, while higher entropy trajectories will be driven neutron rich by antineutrino captures if β is sufficiently large [9].

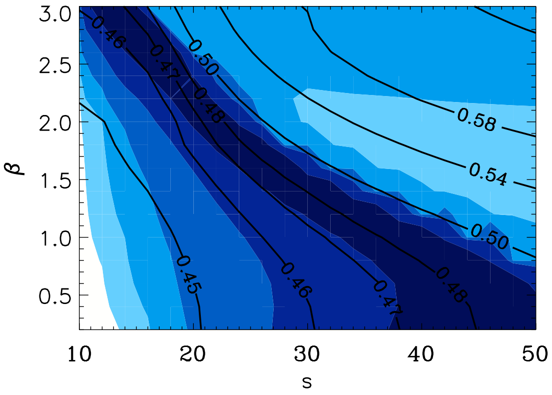

Figure 3: Shows the mass fraction of ^{64}Zn as a function of outflow parameter β and entropy per baryon s/k, for an accretion disk with rate 0.1 $M_{\odot}$/s. Overproduction factors (defined as in [9]) are shown in order from darkest to lightest of greater than 5000, 1000, 100, 10 and 1. Contours of constant Y_e are overlaid on the plot.

Observations of *r*-process elements in metal-poor halo stars [17] and meteorites [18] suggest the operation of two different sites of production for the heavy and light neutron capture elements. Light neutron capture elements are made robustly over the majority of the parameter space we have explored, suggesting the possibility that outflows from very rapid black hole accretion disks may make an important contribution to the galactic abundances of these elements.

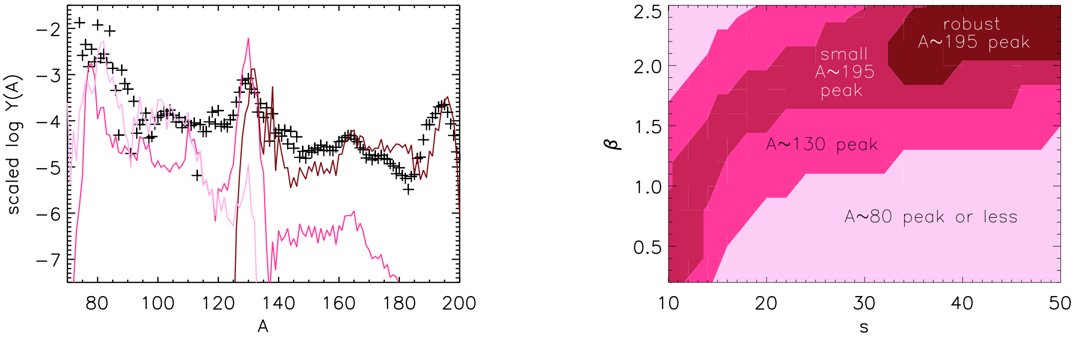

Figure 4: Shows the production of *r*-process nuclei in trajectories from the high accretion rate disk, 10 $M_{\odot}$/s. Scaled abundances versus mass number (left) are shown compared to the solar abundances (crosses) for three trajectories, with parameters $s/k = 30$, $\beta = 1.0$ (light pink), $s/k = 20$, $\beta = 1.4$ (dark pink), and $s/k = 40$, $\beta = 2.0$ (red). The contour plot delineates the regions of s/k, β parameter space that produce each of the *r*-process peaks (right), defined as described in [9].

3. Conclusion

We have studied the types of nucleosynthesis possible in outflows from rapidly accreting disks around black holes. We estimate the neutrino fluxes coming from the disk and include neutrino reactions on nucleons and nuclei in all calculations of the nucleosynthesis. We find that accretion disk outflows may be partially responsible for the ^{56}Ni observed in several gamma-ray burst afterglows. Additionally these outflows, despite their rarity, may be important contributors to the synthesis of certain nuclei, including light r-process nuclei and proton-rich nuclei such as ^{64}Zn.

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