NUCLEOSYNTHESIS IN THE OUTFLOW FROM GAMMA-RAY BURST ACCRETION DISKS

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ABSTRACT

We examine the nucleosynthesis products that are produced in the outflow from rapidly accreting disks. We find that the rate of element synthesis varies dramatically with the degree of neutrino trapping in the disk and therefore the accretion rate of the disk. Disks with relatively high accretion rates such as $\dot{M} = 10 M_\odot$ s$^{-1}$ can produce very neutron-rich nuclei that are found in the $r$-process. Disks with more moderate accretion rates can produce copious amounts of nickel, as well as the light elements such as lithium and boron. Disks with lower accretion rates such as $\dot{M} = 1 M_\odot$ s$^{-1}$ produce large amounts of nickel, as well as some unusual nuclei such as $^{49}$Ti, $^{45}$Sc, $^{64}$Zn, and $^{92}$Mo. This wide array of potential nucleosynthesis products is due to the varying influence of electron neutrinos and antineutrinos emitted from the disk on the neutron-to-proton ratio in the outflow. We use a parameterization for the outflow and discuss our results in terms of entropy and outflow acceleration.

Subject headings: accretion, accretion disks — gamma rays: bursts — nuclear reactions, nucleosynthesis, abundances

Online material: color figures

1. INTRODUCTION

Data on long-duration gamma-ray bursts (GRBs) taken over the last few years have sparked the idea that these events are associated with core-collapse supernovae; for a review see Mészáros (2002). Theoretical models, e.g., the collapsar model (Woosley 1993; MacFadyen & Woosley 1999), suggest that a massive star collapses to an accretion disk surrounding a black hole and that a jet is driven out of the center of the star, leaving behind an escape route for an ultrarelativistic jet that produces the burst itself via internal shocks. Such an event will produce nucleosynthesis, not just in the ultrarelativistic jet, but in the slower outflow that comes off of the accretion disk, as well as through explosive burning.

It is not known whether there are only two types of events, core collapses that make “normal” supernovae with proto-neutron star cores and those that have accretion disks surrounding black holes that produce GRBs, or whether there is a continuum of objects in between these extremes (Heger et al. 2003). The answer to the question, while of interest in its own right, is of crucial importance as far as our understanding of the significance of these objects for element synthesis. Estimates of the rate of GRBs from optical observations show that they occur on a timescale of less than about $10^{-2}$ times the rate of core-collapse supernovae (Podsiadlowski et al. 2004), while radio observations constrain the rate to be less than 5% of the Type Ibc rate (Berger et al. 2003). However, accretion disks that form from stellar collapse may be a more common phenomenon, and consequently element synthesis in outflow from an accretion disk may be much more frequent.

We have less observational evidence for the origin of short-duration GRBs. Two afterglows of short-duration GRBs have been detected thus far, GRB 050509b and GRB 050709. These bursts have been found to be located near galaxies, but no evidence has been found for associated supernovae, pointing to the merging of compact binaries as the source of short-duration GRBs (Hjorth et al. 2005; Gehrels et al. 2005; Villasenor et al. 2005; Fox et al. 2005).

Theoretical calculations have shown that these events may plausibly occur as a result of neutron star mergers (e.g., Ruffert & Janka 1999, 2001; Rosswog & Liebendörfer 2003; Rosswog et al. 2003). Numerical simulations of these events have produced very rapidly accreting disks that surround black holes with rates between $M = 1$ and $10 M_\odot$ s$^{-1}$.

We present a study of the nucleosynthesis products produced from the outflow from accretion disks of $\dot{M} = 0.1, 1$, and $10 M_\odot$ s$^{-1}$ that have black hole spin parameters of $a = 0$. In general, neutrino trapping, as a consequence of higher temperatures, will occur for lower accretion rate disks if the spin parameter is larger. We show an example of the element synthesis from an $a = 0.95, M = 0.1 M_\odot$ s$^{-1}$ disk to illustrate the effect of higher spin. Nucleosynthesis in GRB disk winds has also been studied by Pruet et al. (2003) and Fujimoto et al. (2003, 2004).

Neutrinos can become trapped in the disks, particularly those that are associated with neutron star mergers. The emerging neutrinos annihilate and may drive the burst itself. Therefore, neutrino trapping in these disks is under study by several groups, e.g., Lee et al. (2004), Rosswog et al. (2003), Kohri et al. (2005), Janiuk et al. (2004), and Setiawan et al. (2004).

The neutrinos have an enormous influence on the final elemental abundances, even in cases where the neutrinos are not trapped in the disk. The disks are hot enough to release copious numbers of electron neutrinos and antineutrinos that then interact with free neutrons and protons in the outflow from the disk. Their influence over the neutron-to-proton ratio, together with entropy and therefore heating of the material that leaves the disk, determines the final nucleosynthesis products.

We pay particular attention to the abundance of $^{56}$Ni. $^{56}$Ni drives the light curves of core-collapse supernovae. Since supernova light curves have been detected in GRB light curves, this implies substantial synthesis of $^{56}$Ni either in the outflow from the disk (Pruet et al. 2004b) or in explosive burning (Maeda &
Nomoto 2003). The amount of nickel observed in the light curves corresponds to roughly half of a solar mass (Woosley & Heger 2003).

We also examine some nuclei whose origin is poorly understood but that have large overproduction factors in the outflows from low accretion rate disks, such as $^{44}$Ti, $^{45}$Sc, and $^{64}$Zn (Pruet et al. 2004a). We look at the light $p$-process nuclei such as $^{92}$Mo and $^{96}$Mo. Rapidly accreting disks have been suggested by Fujimoto et al. (2003) as a site for the production of such light $p$-nuclei.

We examine the prospects for producing an $r$-process in high accretion rate disks by way of material that is driven to become neutron-rich by neutrino interactions, as discussed in McLaughlin & Surman (2005). We also discuss conditions under which small amounts of very light nuclei such as lithium and boron can be produced in medium accretion rate disks.

2. DISK AND OUTFLOW MODELS

We use disk models from Popham et al. (1999, hereafter PWF99) for the low accretion rate disk, and from Di Matteo et al. (2002, hereafter DPN02) for the high accretion rate disk. In all cases we consider black hole masses of $3 M_\odot$. The PWF99 models do not include neutrino trapping, and indeed for accretion rates less than $\dot{M} = 0.1 \ M_\odot \ s^{-1}$, there is very little trapping. For higher accretion rates neutrinos do become trapped, and therefore we use the DPN02 models, which include effects of neutrino trapping.

For the outflow we use the trajectories calculated in Surman & McLaughlin (2005) and parameterize the outflow as a wind using

$$|u| = v_\infty \left(1 - \frac{R_0}{R}\right) \beta,$$

where the starting position of the material is $R_0$ and $\beta$ determines the acceleration of the wind. Large $\beta$ represents slow acceleration whereas small $\beta$ represents rapid acceleration. Nucleosynthesis may occur in outflow that does not escape the GRB and instead falls back into the black hole. In all the trajectories for which we consider nucleosynthesis, the material becomes unbound.

In the disk the entropy in units of Boltzmann’s constant is $s/k \sim 10$. Since the material may be heated as it leaves the disk, we consider a range of entropies between $s/k = 10$ and 50.

We use initial $Y_e$ values for our trajectories from the disk as calculated in Surman & McLaughlin (2004) and shown in Figure 1. We use the neutrino fluxes calculated in Surman & McLaughlin (2004) for each of the disk models we use here. In order to calculate the neutron-to-proton ratio in the outflowing trajectory we integrate the flux coming from all parts of the disk, as described in Surman & McLaughlin (2004).

The place where the outflow occurs from the disk will have an impact on the nucleosynthesis, primarily because the neutrino flux varies over the length of the disk. In our calculations we use starting points of $r_0 = 100$ and 250 km from the black hole.

We begin the elemental evolution in the disk outflow by dynamically following the evolution of the electron fraction in the outflow, as described in Surman & McLaughlin (2005; see also McLaughlin et al. 1996). As the temperature drops below $10^{10}$ K, we follow nuclear recombination using an intermediate network calculation (Hix & Thielemann 1999a, 1999b) that includes strong, electromagnetic, and weak interactions. Finally, we use a network that does solely neutron capture, photo-disintegration, $\beta$-decay, charged-current neutrino interactions, and $\beta$-delayed neutron emis-

![Fig. 1.—Electron fraction in the disk, calculated as described in Surman & McLaughlin (2004). These are the initial values of the electron fractions with which we begin our trajectories. The upper, dashed curve represents the $a = 0$, $\dot{M} = 0.1 \ M_\odot \ s^{-1}$ disk, while the lower, solid curve represents the $a = 0$, $\dot{M} = 10 \ M_\odot \ s^{-1}$ disk.

sion (Surman & Engel 2001). The latter is necessary for calculations of the most neutron-rich elements.

3. NUCLEOSYNTHESIS FROM DISKS WITH LOW ACCRETION RATES

Using the outflow trajectories described in the previous section, we present the results of reaction network calculations for outflow from a PWF99 disk with an accretion rate of $\dot{M} = 0.1 \ M_\odot \ s^{-1}$. This is representative of the accretion rates produced by the collapsar model (MacFadyen & Woosley 1999).

In Figure 2 we show the nucleus with the largest mass fraction as a function of entropy and acceleration parameter. As can be seen from the figure, for high entropies $^4$He has the largest mass fraction. The mass fractions of $^4$He range from $X_{^4\text{He}} = 0.30$ to 0.83 in the region where it has a larger mass fraction than any other nucleus.

At high entropy there is a large number density of positrons, which create protons in the outflow through the reaction $e^+ + n \rightarrow p + \nu_e$. At low entropies, there are less positrons since the material is electron degenerate, and therefore fewer protons. In addition, for higher entropy, nuclear statistical equilibrium favors light nuclei until relatively low temperature. Thus the triple-$\alpha$ reaction freezes out of equilibrium before the majority of $\alpha$-particles can reassemble into heavy nuclei. Alpha-rich freeze-out is discussed in Woosley et al. (1973). For low entropies, iron-peak nuclei assemble at high temperature, before the triple-$\alpha$ reaction falls out of equilibrium.

For low entropies we find that the nucleus with the largest mass fraction is $^{62}$Ni. The mass fraction in the region where $^{62}$Ni dominates ranges from $X_{^{62}\text{Ni}} = 0.25$ to 0.75.

In the bottom panel of Figure 2 we show the nucleus with the largest mass fraction excluding $^4$He. It is interesting to note that when large amounts of $^4$He are produced, $^{56}$Ni is produced as well. For more rapid accelerations heavier isotopes are produced, and for entropies of between $s/k = 30$ and 40 we see considerable $^{66}$Zi.

Additional clues to the overall abundance pattern are given by the electron fraction, $Y_e = 1/(1 + n/p)$, where $n/p$ is the neutron-to-proton ratio. This is shown as the solid lines in Figure 3. In addition to the effect of the entropy on the electron fraction as already discussed, there is a significant change due to the acceleration...
of the material. Slowly accelerating material (high $\beta$) has more time to approach the high-equilibrium electron fraction (as set by the entropy) than the rapidly accelerating material, which retains some of the neutron richness of the disk. In addition, with fast acceleration (i.e., low $\beta$) there is little time for the neutrinos flowing off of the disk to interact with the outflow material. With slow acceleration, however, there is more time and the electron fraction increases.

In this relatively low accretion rate disk the neutrinos are not trapped, and therefore the neutrinos emitted from the disk are coming directly from an inverse $^{12}$C-decay. The electron neutrinos interact with the outflowing matter to raise the electron fraction through the reaction $\nu_e + n \to p + e^-$. The effect of the neutrinos on the electron fraction here is relatively small, of the order of $1\%-5\%$; however, this influence grows significantly in trajectories from disks with higher black hole spin parameter $a$ and higher accretion rates.

In Figure 3 the $^{56}$Ni abundance is shown. The largest abundance comes from moderate entropies and relatively slow outflows. Pruet et al. (2004a) suggested that for those trajectories that produce considerable $^{56}$Ni, an unusual nucleosynthesis pattern is produced as well, including traditionally underproduced nuclei such as $^{45}$Sc, $^{49}$Ti, and $^{64}$Zi. Here we extend the results of that study to include a larger range of trajectories that also include the effects of neutrino scattering. The results are shown in Figure 4, which is a contour plot of the overproduction factors for these nuclei, where we define overproduction factor as in Pruet et al. (2004):

$$O(f) = \frac{M_{\text{wind}}}{M_{\text{SN ejecta}}} \times \frac{X_{\text{wind}}}{X_{\odot}},$$

(2)

where $X_{\odot}$ is the observed solar mass fraction of the nucleus, $X_{\text{wind}}$ is our calculated mass fraction in the outflow, $M_{\text{SN ejecta}}$ is the mass ejected in a supernova explosion, and $M_{\text{wind}}$ is the total mass contained in the outflow from the accretion disk. We take the scaling $M_{\text{wind}}/M_{\text{SN ejecta}}$ to be 0.1 in order to reflect that fact not all the ejecta will come from the wind. For a particular model of a GRB that predicts an $M_{\text{wind}}/M_{\text{SN ejecta}}$ value, our results must...
be scaled accordingly. All three of these nuclei have large over-
production factors that extend in a band from low entropy, slow
acceleration to high entropy, fast acceleration. The results cor-
relate with the electron fraction.

In Figures 5 and 6 we consider also the light p-process nuclei,
for which there is no universally agreed upon production site. It
has been suggested in Fujimoto et al. (2003) that these nuclei
can be produced in an accretion disk. We show $^{92}$Mo and $^{94}$Mo,
as well as $^{84}$Sr, $^{78}$Kr, and $^{74}$Se, in the context of the outflow from
the low accretion rate disks. We find overproduction factors for
$^{92}$Mo of greater than 1000 along the same band that over-
produces large amounts of $^{45}$Sc, $^{49}$Ti, and $^{64}$Zn.

The largest overproduction factors for zinc occur for electron
fractions at just slightly less than one-half. This is similar to the
$\alpha$-rich freezeout of the neutrino-driven wind of the supernova
(Fuller & Meyer 1995; Hoffman et al. 1996), but the over-
productions we observe are larger. Overproduction factors around
100 occur for conditions that are just slightly proton-rich, similar
to what is observed in the hot bubble of the supernova (Pruet
et al. 2005; Frohlich et al. 2006), although again we find a larger
effect. There is another band of large overproduction factor at
slow outflow, which is due to the influence of neutrino capture on
nucleons. It is interesting to note that in the observations of
Cayrel et al. (2004) the ratios [Zn/Fe] and [Zn/Mg] increase with
decreasing metallicity. While the origin of zinc is a matter of de-
bate, magnesium is thought to be primarily produced in core-
collapse supernovae.

Other nuclei that have large overproduction factors in these
disks include $^{46}$Ti, $^{59}$Co, $^{88}$Sr, $^{90}$Zr, $^{74}$Se, and $^{63}$Ni.

As mentioned above, the black hole spin parameter increases
the degree of trapping in the disk. In Figure 7 we show the $^{56}$Ni
abundance for a PWF99 disk of $M = 1 \, M_\odot$ s$^{-1}$ and $a = 0.95$.
When compared with the electron fractions of the $a = 0$ model
shown in Figure 3, it can be seen that the trapped neutrinos sig-
ificantly change the neutron-to-proton ratio.

4. ELEMENT SYNTHESIS FROM MEDIUM
ACCRETION RATE DISKS

Disks with accretion rates of $M = 1 \, M_\odot$ s$^{-1}$ are predicted
by simulations of neutron star merger events. For these accre-
disk the electron neutrinos are trapped in the disk. The

Fig. 5.—Overproduction factors of $^{92}$Mo and $^{94}$Mo in the outflow of the low
accretion rate disk, $\dot{M} = 0.1 \, M_\odot$ s$^{-1}$. Dark shaded regions from darkest to light-
est correspond to overproduction factors of 1000, 100, 10, and 1. [See the elec-
tronic edition of the Journal for a color version of this figure.]

Fig. 6.—Overproduction factors of the p-process nuclei $^{84}$Sr, $^{78}$Kr, and $^{74}$Se in
the outflow of the low accretion rate disk, $\dot{M} = 0.1 \, M_\odot$ s$^{-1}$. Dark shaded regions
from darkest to lightest correspond to overproduction factors of 1000, 100, 10,
and 1. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 7.—Mass fraction of $^{56}$Ni in the outflow of a low accretion rate disk,
$\dot{M} = 0.1 \, M_\odot$ s$^{-1}$, with black hole spin parameter $a = 0.95$. Dark shaded regions
from darkest to lightest correspond to mass fractions of greater than 0.5, 0.4, 0.3,
0.2, and 0.1. [See the electronic edition of the Journal for a color version of this
figure.]
antineutrinos are trapped as well, but in a much smaller region than the neutrinos. The number of electron neutrinos overwhelms that of the electron antineutrinos coming from the disk, although the antineutrinos have higher temperature than the neutrinos. For the DPN02 model, the neutrino temperatures range from 4.1 to 5.2 MeV and the antineutrino temperatures range from 5.0 to 5.4 MeV (Surman & McLaughlin 2004). Due to the overwhelming numbers of neutrinos in the outflowing material, the reaction \( \nu_e + n \rightarrow p + e^- \) creates very proton-rich matter.

For the lower accretion rate disks considered in the last section, even the one with a nonzero black hole spin parameter, the neutrinos make a \( \lesssim 30\% \) difference in the final value of the electron fraction, but for the disk considered in this section the neutrinos dominate the determination of the electron fraction and create a proton-rich environment in the disk outflow for trajectories with all accelerations and entropies.

In the top panel of Figure 8 we show the nucleus with the largest mass fraction for a range of accelerations and entropies. As can be seen from the figure, helium again dominates the mass fraction for larger entropies, with mass fractions of \( \sim 0.3 \)–0.6. In the bottom panel of Figure 8 we show the nucleus with the largest mass fraction excluding helium; again large amounts of \( ^{56}\text{Ni} \) are produced as well, with \( X_{^{56}\text{Ni}} \sim 0.2 \) to \( \sim 0.7 \), as shown in Figure 9.

It can be seen from Figure 9, which shows the electron fractions in the outflow, that the material becomes very proton-rich, with \( Y_e > 0.7 \) for slow accelerations. Given such proton-rich material, it is interesting to investigate whether very light nuclei such as lithium and boron are formed as well in the disk outflow.

TABLE 1

| \( s \) | \( \beta \) | \( Y_e \) | \( X_{^{4}\text{He}} \) | \( ^{7}\text{Li}/H \) | \( ^{11}\text{B}/H \) |
|-------|------|--------|--------|----------|--------|
| 10    | 2.5  | 0.560  | 0.102  | \( 2.2 \times 10^{-9} \) | \( 6.7 \times 10^{-10} \) |
| 15    | 2.5  | 0.641  | 0.191  | \( 9.6 \times 10^{-10} \) | \( 1.6 \times 10^{-10} \) |
| 30    | 2.5  | 0.767  | 0.314  | \( 1.6 \times 10^{-10} \) | \( 1.1 \times 10^{-11} \) |
| 40    | 2.5  | 0.779  | 0.372  | \( 3.7 \times 10^{-11} \) | \( 2.0 \times 10^{-12} \) |

(Ryan et al. 2000). However, only a fraction of the baryons in the universe will pass through massive stars, so the subject bears further investigation with a Galactic chemical evolution study.

It is generally thought that \( ^{11}\text{B} \), which has a solar mass fraction of \( X_{^{11}\text{B}} \approx 5 \times 10^{-10} \), may be produced by a combination of cosmic-ray spallation and the neutrino process, with estimates of up to 30% for the latter contribution (Vangioni-Flam et al. 1996). For a discussion of \( ^{7}\text{LiBeB} \) from a related site, hypernova ejecta, see Fields et al. (2002).

In Figure 9 the mass fraction of \( ^{56}\text{Ni} \) is plotted. Most of the outflowing material becomes \( ^{56}\text{Ni} \) for moderate entropies \( s/k \approx 30 \), moderate outflows \( \beta \approx 1.5 \), or points in between. Little nickel is produced for fast outflows and low entropies, or for high entropies and slow outflows. Our study suggests that if collapsing stars form disks that accrete at a rate of \( M = 1 M_\odot \) s\(^{-1} \) or more slowly with higher spin parameter, then this range of acceleration and entropy would be required to explain the nickel inferred from the GRB light-curve bumps.
neutron-rich matter that will adiabatically decompress and can also form an r-process.

For such high accretion rates the electron antineutrinos are trapped in a fairly large region, within a radius of 158 km from the black hole, although the electron neutrinos are trapped in a larger region within \( r_{\text{disk}} \sim 240 \) km (Surman & McLaughlin 2004). The temperature of the electron antineutrinos is therefore higher, 3.6 MeV \(< T_{e} < 6.9 \) MeV as compared with 2.4 MeV \(< T_{e} < 5.9 \) MeV. The neutrinos coming from the surface of the disk interact with the outflowing matter. Because the antineutrinos are more energetic than the neutrinos, the material is driven neutron-rich through the reaction \( \bar{\nu}_{e} + p \rightarrow n + e^{+} \), which has a larger flux-averaged cross section than \( \nu_{e} + n \rightarrow p + e^{-} \).

The degree of neutron richness depends on the neutrino fluence: the time-integrated neutrino flux experienced by a mass element in the outflow. For more slowly accelerating outflows the antineutrinos have more time to interact, creating more neutrons. Conversely, for more rapid accelerations there is little time for neutrino interactions and the electron fraction is higher.

We note that for lower entropies, the material is electron degenerate with very few positrons, and therefore has a large neutron-to-proton ratio regardless of its interactions with neutrinos or antineutrinos. We have also included the \( \alpha \)-effect as discussed in Meyer et al. (1998).

In Figure 11 we show the peaks that are primarily formed in the rapid neutron capture process. We calculate the ratios between the abundances in each peak region as in Meyer & Brown (1997):

\[
\frac{130}{80} = \frac{\sum_{A=135}^{A=155} Y_{A}}{\sum_{A=85}^{A=125} Y_{A}}, \quad \frac{195}{130} = \frac{\sum_{A=195}^{A=200} Y_{A}}{\sum_{A=135}^{A=200} Y_{A}}. \tag{3}
\]

The unshaded region is where the ratio 130/80 is less than 0.07; only the \( A = 80 \) peak or less is formed for these trajectories. The ratio 130/80 is greater than 0.07 and the ratio 195/130 is less than 0.3 for trajectories in the next region, labeled \( A = 130 \) as it is this peak that primarily forms. The darkest shaded region is where the ratio 195/130 is greater than 0.3 and the heaviest elements are formed. In the intermediate shaded region, the ratio 195/130 is close to but below 0.3; in these trajectories the \( A = 195 \) peak has formed, but the relative peak heights are not in agreement with the observed solar r-process abundances. A robust r-process occurs in the slow accelerating trajectories.

The abundance pattern for two trajectories, one with slow acceleration and one with low entropy, is shown in Figure 12.

For high entropy, the second, \( A = 130 \), r-process peak is formed without the \( A = 195 \) peak from somewhat more quickly accelerating trajectories. And for very fast accelerations we find that only the \( A = 80 \) peak is formed. It is interesting to note that both meteoritic data (Qian et al. 1998) and observations of metal-poor halo stars (e.g., Sneden et al. 2003) suggest two r-process sites. One of these forms the nuclei above the second peak, and one of these forms the nuclei below. The meteoritic data suggest that the third peak is associated with a relatively frequently occurring event, such as core-collapse supernovae. Core-collapse supernovae have been studied extensively as r-process sites beginning with Meyer et al. (1992) and Woosley et al. (1994), although at present there is no completely self-consistent model that produces these elements without invoking new particle physics. The meteoritic data also hint that the low-mass r-process nuclei are associated with a lower frequency event, such as a neutron star merger (Argast et al. 2004).

Since the abundance distribution of the high-mass nuclei in low-metallicity halo star tracks well the solar system abundance,
such an event should operate early in the evolution of the universe. An explosion of a massive star, such as in the collapsar model, would also operate early in the evolution of the universe. However, this model currently predicts lower accretion rate disks than the ones from which we find the r-process being produced. In order to use this model to produce r-process nuclei, the disk would need to pass through a stage in which it is very rapidly accreting or has a high black hole spin parameter.

The solar system abundances of lower mass r-process nuclei do not track the abundance pattern measured in metal-poor stars well. This suggests that the type of event that produces these nuclei does not necessarily operate early in the evolution of the universe, or is at least less frequent. If the lower mass r-process nuclei were to come from disks associated with neutron star mergers, then the outflow acceleration would be fast, $\beta \sim 1$, for most possible values of entropy in the outflow. In Figure 13 we plot the abundance pattern for two trajectories with entropies $s/k = 30$ and 45, both with $\beta = 1.0$.

6. CONCLUSIONS

We find that a large range of nuclesynthesis may occur in the outflow from gamma-ray burst accretion disks. For disks of $M = 0.1 - 1 M_\odot$ s$^{-1}$, most of the element synthesis makes helium and $^{56}$Ni, except for low-entropy and/or slow-acceleration trajectories.

There is a significant, diagonal region of parameter space extending from slow-outflow, low-entropy to fast-outflow, high-entropy trajectories, where nuclei such as $^{45}$Sc, $^{49}$Ti, $^{64}$Zn, $^{92}$Mo, and $^{94}$Mo are overproduced by factors of 100–1000 in the low accretion rate models. These low accretion rates are typical of the collapsar model. Disk winds can significantly contribute to the Galactic inventory of these nuclei if the rate of supernovae that produce disks is $>10^{-2}$ times that of the rate of core-collapse supernovae. This rate can be considerably higher than the limits on GRBs of $\lesssim 10^{-2}$ since not all disks may produce bursts.

In the outflow from both of these disks significant $^{56}$Ni is produced, with mass fractions of up to 0.7. Low accretion rate disks require slow outflow and moderate entropy, $s/k \sim 20$, to synthesize considerable $^{56}$Ni, while moderate accretion rate disks can synthesize considerable nickel with faster outflow for similar entropies. Introducing a nonzero spin parameter to the disk creates more $^{56}$Ni at lower entropies and outflow accelerations, due to the increased influence of the neutrinos.

The moderate accretion rate disks can also make the $N = 50$ peak of the r-process for low entropy and fast outflow. The moderate accretion rate disks are predicted to come from neutron star mergers. Observational evidence is consistent with such an infrequently occurring event that synthesizes the $N = 50$ peak.

For the high accretion rate disks the majority of the parameter space produces an r-process. The $A = 195$ peak is synthesized only for slowly accelerating outflows, although the $A = 130$ peak is made more robustly. In the very fast acceleration, high entropy trajectories we find only the first peak of the r-process.

Future studies of the hydrodynamics of the outflow from accretion disks surrounding black holes will determine which of these patterns of element synthesis occurs in nature.

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