Prospects for obtaining an $r$ process from Gamma Ray Burst Disk Winds

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We discuss the possibility that $r$-process nucleosynthesis may occur in the winds from gamma ray burst accretion disks. This can happen if the temperature of the disk is sufficiently high that electron antineutrinos are trapped as well as neutrinos. This implies accretion disks with greater than a solar mass per second accretion rate, although lower accretion rates with higher black hole spin parameters may provide viable environments as well. Additionally, the outflow from the disk must either have relatively low entropy $s \sim 10$ or the initial acceleration of the wind must be slow enough that it is neutrino and antineutrino capture as opposed to electron and positron capture that sets the electron fraction.

1. INTRODUCTION

The $r$-process of nucleosynthesis is responsible for over half the elements with $A > 100$ but to date no self-consistent model for an astrophysical site for the production of these elements has been identified. The two candidates most discussed in the literature are the neutrino driven wind of Type II supernovae [12] and ejecta from neutron star mergers [3-5]. The former site is attractive because it occurs on a timescale such that it could reasonably account for observations in metal poor halo stars e.g. [6] and could produce roughly the right amount of material [2]. Furthermore, the neutrinos from the protoneutron star set the electron fraction to a relatively low value and this, combined with the high entropy, makes it a promising site. Although attempts to produce the $r$-process elements this way initially succeeded, subsequent refining of the models indicated that the conditions were a near miss, e.g. [7,8]. In addition, self-consistent inclusion of the neutrinos in a reaction network demonstrated that electron neutrino capture on neutrons during the course of alpha particle formation drove the electron fraction up to values unacceptable to the $r$-process [9].

The other primary candidate for the production of $r$-process elements, the ejecta from neutron star mergers, is a viable candidate for producing some of these elements. However as a dominant $r$-process site, it would be difficult to reconcile with the observations from

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metal poor stars, e.g. [10]. If the $r$ process has more than one component, as suggested by meteoritic evidence [11] and observations of the low mass end of the $r$-process distribution, then neutron star mergers could well contribute.

Here we discuss another possible site for the $r$ process, which is in the winds from accretion disks in gamma ray bursts. Gamma ray bursts represent an emerging new area in nucleosynthesis research. The leading candidate sites for these objects are rare supernovae, such as a collapsars [12], and for the short bursts, neutron star-neutron star mergers [13,14]. In either case, the system likely forms an accretion disk surrounding a black hole. Some nucleosynthesis will occur in the jet [15], some will occur as explosive burning [16] and still more will occur in the outflow, perhaps a wind [12,17], from the accretion disk. The rate of gamma ray bursts is estimated to be quite low, $\sim 10^{-5}$ per year in the Galaxy, e. g. as discussed in [18]. However since their origin is not yet fully understood, they may well represent one end of a continuum of objects. It is therefore difficult to estimate the rate of ejection of their nucleosynthesis products into the interstellar medium.

![Diagram](image)

Figure 1. Electron neutrino and antineutrino surfaces in a $\dot{M} = 1 \text{M}_\odot/\text{s}$, $a = 0$ (a, on the left) and a $\dot{M} = 10 \text{M}_\odot/\text{s}$, $a = 0$ (b, on the right) accretion disk. The solid line shows the density scale height of the disk.

The possibility of obtaining an $r$ process in an accretion disk wind is closely tied to understanding the neutrinos which are emitted copiously from the disk. Neutrinos are involved in all charge-changing interactions

$$e^- + p \leftrightarrow \nu_e + n \quad (1)$$

$$e^+ + n \leftrightarrow \bar{\nu}_e + p \quad (2)$$

both in the disk and in the outflow from the disk. In order to make the outflow neutron rich, either electron capture or electron antineutrino capture must dominate. In the case of disks with high accretion rates where both the neutrinos and the antineutrinos are
trapped (as in Fig. 1), it is antineutrino capture that can create conditions conducive to forming the r-process elements.

2. NEUTRINO TRAPPING IN THE DISK

Whether the neutrinos in the accretion disk are trapped or not depends on the parameters that characterize the disk, such as the accretion rate $\dot{M}$, the viscosity $\alpha$ and the black hole spin parameter $a$. In Fig. 1 we show the trapped regions for neutrinos and antineutrinos which we have calculated from the disk models of DiMatteo, Perna and Narayan (2002) [19]. In the outer regions of the disk, neutrinos and antineutrinos are produced by the inverse beta decay processes (forward reactions in Eqs. 1 and 2) and the neutrinos escape freely. However, toward the center of the disk, the electron neutrinos first become trapped, and then the electron antineutrinos become trapped as well, enabling the backward reactions in Eqs. 1 and 2 to come into equilibrium with the forward processes. In the higher accretion rate model, $\dot{M} = 10 M_\odot/\text{s}$, $a = 0$ these regions are larger than for the more moderate accretion rate model $\dot{M} = 1 M_\odot/\text{s}$, $a = 0$. In particular the region enclosed by the antineutrino surface has expanded, although the antineutrinos still decouple considerably further in than the neutrinos. More detail on calculations of the disk neutrinos can be found in [20].

We use the neutrino and antineutrino spectra emitted from every radius on the disk surface to determine the neutrino and antineutrino fluxes at every point above the disk. The spectra from the electron neutrinos and antineutrinos at about 200 km above the two disks shown in Figs. 1a and 1b can be seen in Figs. 2a and 2b. For the lower accretion rate disk, the electron neutrino flux far dominates the electron antineutrino flux. Although the
electron antineutrinos which come from the surface shown in 2a have higher temperature than the neutrinos, the area of the antineutrino surface is very small, so the number of antineutrinos is not large and a significant number of those seen in 2a are coming directly from inverse beta decay in the free streaming region. In the higher accretion rate disk, the situation is quite different. Because the antineutrino surface has grown, and the antineutrinos have higher temperature than the neutrinos, the antineutrino flux is larger and more energetic than the neutrino flux. In these models the electron neutrino temperature at the neutrino surface varies with position but is around $T_{MeV} \sim 2.5$ to $T_{MeV} \sim 4.5$ while the temperature at the antineutrino surface is around $T_{MeV} \sim 3.6$ to $T_{MeV} \sim 5.1$ [20]. In even lower accretion rate disks (not shown here), e.g. Popham, Woosley, Fryer (1999) [21], $\dot{M} = 0.1 M_\odot / s$, $a = 0.95$, the neutrinos are barely trapped and the antineutrinos are not trapped at all.

3. OUTFLOW FROM THE DISK

We study the effect of the charge-changing interactions on the outflow from the disk by using a parameterization for the wind, as in [22]. The velocity is taken to be

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

where $R = (z^2 + r_c^2)^{0.5}$ for the first, vertical part of the trajectory and the starting position of the material is $R_0$. Here $z$ is the vertical coordinate above the disk, and $r_c$ is the cylindrically radial component along the disk. The parameter $\beta$ controls the acceleration of the wind; for lower $\beta$ the wind accelerates faster. In terms of the neutrinos, larger $\beta$
means more time for the neutrinos to influence the composition of the outflow. In Fig 3, we show outflow from two different types of disk models, DPN $\dot{M} = 10M_\odot/\text{s}$ and $\dot{M} = 1M_\odot/\text{s}$.

It can be seen from these figures that the neutrinos influence the electron fraction in opposite directions in the two models. In the more moderate accretion rate model $\dot{M} = 1M_\odot/\text{s}$, $a = 0$, the large flux of neutrinos shown in Fig 2 raises the electron fraction to quite high values. However in the higher accretion rate model, $\dot{M} = 10M_\odot/\text{s}$, $a = 0$, the large flux of antineutrinos decreases the electron fraction to quite low values, even in the case of a high entropy outflow. Also interesting is the low entropy case in Fig. 3b, where the electron fraction remains quite low regardless of the influence of the neutrinos. This is due to the electron degeneracy of the material at a high density and low entropy.

In Fig. 4, we survey a number of different outflows, by plotting the electron fraction measured at a temperature of 1 MeV against entropy for several different values of $\beta$. In all cases the final outflow velocity is $v_\infty = 10^4\text{km s}^{-1}$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Electron fractions in the outflow measured at a temperature of 1 MeV for two different disk models $\dot{M} = 1M_\odot/\text{s}$, $a = 0$ (a, on the left) and $\dot{M} = 10M_\odot/\text{s}$, $a = 0$ (b, on the right) are shown. Various values of the acceleration parameter $\beta$ are plotted against entropy per baryon in the outflow.}
\end{figure}

The plus signs show the effect of a slow outflow parameter $\beta = 2.5$. In this case the neutrino and antineutrino capture rates completely overwhelm the electron and positron capture rates, and the system finds a weak equilibrium such that

$$Y_e = \frac{1}{1 + \frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}}$$  \hspace{1cm} (4)

where $\lambda_{\bar{\nu}_e p}$ is antineutrino capture on protons and $\lambda_{\nu_e n}$ is neutrino capture on neutrons.

Again we see that a slow outflow from a high accretion rate disk will produce a low electron fraction due to the neutrino interactions, although for any outflow a low entropy will also create a low electron fraction. For the lower accretion rate disk and slow outflows,
the neutrinos always make the material more proton rich and in fact it is only the case of low entropy and minimal neutrino interactions that produces a low electron fraction.

4. NUCLEOSYNTHESIS

Although there are two regions of parameter space which will produce very neutron rich winds, this is not a guarantee of a successful $r$ process, so in this section we investigate this possibility. We take the high accretion rate model $\dot{M} = 10 M_\odot / s$, $a = 0$ and an outflow with a fairly low entropy, $s=10$ and $\beta = 0.8$ and a final velocity of $3 \times 10^4$ km s$^{-1}$. This is the same trajectory as shown as the solid line in Fig. 3b. Our calculation indicates that the low entropy trajectories do produce an $r$ process as shown in the solid line in Fig. 5. The dashed line shows a calculation with a higher entropy, $s = 40$, but a slower

![Figure 5.](image)

Figure 5. Shows two $r$-process nucleosynthesis calculations, both in outflows from a $\dot{M} = 10 M_\odot / s$, $a = 0$ accretion disk. We show a low entropy $s = 10$ outflow with $\beta = 0.8$ and $v_\infty = 3 \times 10^4$ km s$^{-1}$ as the solid line and we show a high entropy outflow, $s = 40$ but with a slow acceleration parameter, $\beta = 2.5$ and $v_\infty = 3 \times 10^4$ km s$^{-1}$ as the dashed line. The crosses show the measured solar abundances.
outflow acceleration $\beta = 2.5$ so that the neutrinos have greater influence. Note that in neither of these calculations is there an “alpha effect” \cite{23} and this is due to the high outflow velocity at the time alpha particles are forming.

While the higher accretion rate disks may be a viable site for the $r$ process, moderate accretion rates disks such as $\dot{M} = 1 \, M_\odot / \text{s}, \, a = 0$ will produce much higher electron fractions. In Fig. 4, it can be seen that the material which has been irradiated by a large neutrino fluence because of its slow acceleration ($\beta = 2.5$) is very proton rich. This type of outflow will produce primarily nickel, but it will also produce some nuclei on the proton rich side of the valley of beta stability as well, such as $^{58}\text{Cu}$, $^{59}\text{Zn}$, $^{50}\text{Fe}$ and $^{52}\text{Fe}$. For still lower accretion rate models, such as $\dot{M} = 0.1 \, M_\odot / \text{s}, \, a = 0.95$ the outflow will have an electron fraction which is closer to $Y_e = 0.5$, although the neutrinos may drive the electron fraction up to as much as $Y_e = 0.6$. Winds of this type with entropies of order $s \sim 30$ may have an unusual nucleosynthesis pattern with large overproduction factors of elements such as $^{42}\text{Ca}$ and $^{45}\text{Sc}$, $^{46}\text{Ti}$, $^{49}\text{Ti}$, $^{63}\text{Cu}$, $^{64}\text{Zn}$ as discussed in \cite{24}. Lower spin parameter models are discussed in \cite{25}.

5. CONCLUSIONS

The winds from accretion disks surrounding black holes in the context of gamma ray bursts are a new arena in which to investigate nucleosynthesis. The most important parameters which determine the elements formed in the outflow from the disk are the accretion rate and black hole spin parameter. This is because the density and temperature of the disk determine where the neutrinos and antineutrinos become trapped. Neutrinos become trapped before antineutrinos, and in some disks only neutrinos are trapped, not antineutrinos. In these disks the wind is proton rich, from the reaction $\nu_e + n \rightarrow e^- + p$, and produces considerable nickel-56, but also elements on the proton rich side of the valley of beta stability. However as the accretion rate increases, a sizable region of trapped antineutrinos can develop, and these antineutrinos cause the wind to become neutron rich. This happens because the higher temperature antineutrinos cause $\bar{\nu}_e + p \rightarrow e^+ + n$ to be faster than the corresponding reaction for neutrinos. If the outflow is is slow enough, for example in our parameterization at around $\beta = 2.5$, or has low entropy $s \sim 10$, then the electron fraction is sufficiently low that $r$-process elements are produced in the outflow.

REFERENCES