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Can a Large Neutron Excess Help Solve the Baryon Loading Problem in Gamma-Ray Burst Fireballs?

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We point out that the baryon loading problem in gamma-ray burst (GRB) models can be ameliorated if a significant fraction of the baryons which inertially confine the fireball is converted to neutrons. A high neutron fraction can result in a reduced transfer of energy from relativistic light particles in the fireball to baryons. The energy needed to produce the required relativistic flow in the GRB is consequently reduced, in some cases by orders of magnitude. A high neutron-to-proton ratio has been calculated in neutron star-merger fireball environments. Significant neutron excess also could occur near compact objects with high neutrino fluxes.

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In this Letter we show how the baryon loading problem can be alleviated in certain gamma-ray burst (GRB) models when significant numbers of baryons are converted to neutrons. Interestingly, many of the proposed GRB “central engines” involve compact objects which are themselves highly neutronized, or which are accompanied by intense neutrino fluxes. Weak interactions induced by these neutrino fluxes can result in significant proton-to-neutron conversion, especially if resonant neutrino flavor transformation takes place [1–3].

Inferences of the energetics and spectral observations of GRBs imply (i) total energies in gamma rays approaching $10^{53}$ ergs for the most energetic events (in the absence of beaming), and (ii) large Lorentz factors of the progenitor fireball ($\gamma \sim 10^5$) for a recent review, see Ref. [4]). Excessive baryon pollution of the fireball precludes attainment of these features for many GRB models. This is a consequence of the conversion of radiation energy in the electron/positron/photon fireball to kinetic energy in baryons [5,6]. However, the relatively small cross sections characterizing the interactions of neutrons with the electron/positron/photon plasma may afford a solution to this problem. This can be seen by considering the fictitious limit of completely noninteracting neutrons. Imagine that protons inertially tether an electron/positron/photon fireball via photon Thomson drag on $e^\pm$, which in turn influences protons through Coulomb interactions. If these protons were suddenly converted to noninteracting “neutrons,” then the fireball would expand relativistically, leaving behind the baryonic component. Real neutrons can approximate this limit as they interact with the electron/positron/photon plasma only via the neutron magnetic dipole moment. These cross sections are small compared to the Thomson cross section $\sigma_T$: neutron-electron (positron) scattering has $\sigma_{ne} \sim 10^{-7}\sigma_T$ [7]; neutron-photon scattering has $\sigma_{n\gamma} \sim 10^{-12}\sigma_T$ [8].

However, the real limit on the efficacy of this mechanism is the strong interaction neutron-proton scattering which will dominate the energy transfer process when conversion of neutrons to protons is incomplete. Therefore, the degree to which the baryon loading burden can be lifted in our proposed mechanism will depend on the neutron excess in the fireball environment. Here we will measure the neutron content of the plasma in terms of the electron fraction $Y_e$, the net number of electrons $(n_e - n_{e^-})$ per baryon, or in terms of the neutron-to-proton ratio $Y_p = 1/(n/p + 1)$.

We note that although previous studies have invoked neutrino oscillations to attempt a baryon loading problem solution [9,10], none has exploited the $Y_e$-changing aspect of the weak interaction.

To go beyond the simplistic picture of noninteracting neutrons, we can consider a two-component [(i) neutrons, and (ii) protons/$e^\pm$/photons] plasma in the context of a homogeneous fireball with initial radius, temperature, Lorentz factor, and electron fraction, $R_0, T_0, \gamma_0$, and $Y_{e0}$, respectively. Numerical and analytic work has shown the following simple scaling laws for such a configuration [6,11]:

\[
\begin{align*}
\text{for } R < \eta R_0/\gamma_0 & \Rightarrow \\
& \frac{\gamma}{\gamma_0} = \frac{R_0}{R}, \\
& T = T_0(R_0/R), \\
& \text{for } R > \eta R_0/\gamma_0 \Rightarrow \gamma = \eta.
\end{align*}
\]

As a matter of convenience we will take the scaling to be such that $\gamma_0 = 1$. In Eq. (1), the ratio of energy in radiation $\mathcal{E}$ to total baryon rest mass $M$ is $\eta \equiv \mathcal{E}/M$.

One can relate $\eta$ to the entropy per baryon, $s$, using the number density of baryons $N = \rho_b/m_p = \rho_{\text{had}}/m_p\eta$ where $\rho_b$ is the baryon component rest mass energy density and $m_p$ is the proton rest mass. Using this relation, and noting that in terms of the proper entropy density $S$, the entropy-per-baryon is $s = S/N$, the relation between $s$, $\eta$, and the temperature $T_0$ is $s \approx 1250\eta (1 \text{ MeV}/T_0)$.

For a large enough $\eta$, baryon loading is unimportant [5]. In fact, when $\eta \approx 10^{3}(E/10^{52} \text{ erg})^{2/3}(10^7 \text{ cm}/R_0)^{2/3}$, the fireball becomes optically thin before transferring its energy to kinetic energy in baryons (here $E$ is the total energy of the fireball).

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Written in terms of time $t$ as measured in a frame comoving with the fireball the above relations imply

$$R = R_0 e^{t/\tau_{\text{dyn}}}, \quad \gamma = e^{t/\tau_{\text{dyn}}}, \quad T = T_0 e^{-t/\tau_{\text{dyn}}}$$

for $\gamma < 1$. Here the dynamic time scale is defined to be the initial light crossing time, $\tau_{\text{dyn}} \equiv R_0/c$. In fireballs resulting from neutron star mergers, for example, $\tau_{\text{dyn}} \sim 2.7 \times 10^{-5} \text{ s}$, corresponding to an $R_0$ of 8 km [12].

A particle comoving with the expanding plasma experiences a 4-acceleration $a^4$, with magnitude $\sqrt{a^4} \rho_d = dy/dR$. As noted above, the force that drags the neutrons along with the expanding plasma arises principally from $n-p$ collisions. The relative contribution to the total force on the neutrons from collisions with electrons and positrons is roughly $F_{n-e}/F_{n-p} \sim m_e n_e \sigma_{n \gamma}/m_p n_p \sigma_{np} \leq 10^{-10}(s/Y_e)$ and is small for the conditions we consider. The neutron-photon cross section is small enough $(\sigma_{n \gamma} \sim 10^{-36}(E_\gamma/(1 \text{ MeV}))^2 \text{ cm}^2$ where $E_\gamma$ is the photon energy in the neutron rest frame [8]) that $n-\gamma$ interactions are negligible.

The relations in Eqs. (1) imply that an inertial observer with time coordinate $t'$ initially (at $t' = 0$) comoving with the plasma sees the plasma accelerate according to $\gamma v = t'/\tau_{\text{dyn}}$. Hereafter we adopt natural units where $c = 1$. If we denote by $\tau_{\text{coll}}$ the frequency of neutron/proton collisions (per neutron), we expect that the two components of the plasma will achieve a relative velocity given by $v_{\text{rel}} = 2\tau_{\text{coll}}/\tau_{\text{dyn}}$, where the factor of 2 arises from the approximate angle independence of the neutron-proton scattering cross section and the near equality of the neutron and proton masses. An equivalent expression is found if one considers the force on the neutrons from collisions with protons [13]. It is clear then that when $\tau_{\text{dyn}} \gg \tau_{\text{coll}}$ the neutrons are coupled to the rest of the plasma. However, decoupling occurs as these two time scales become comparable. Since the baryon number density in the plasma frame decreases as $e^{-3t/\tau_{\text{dyn}}}$, decoupling will occur quickly, i.e., on a time scale shorter than $\tau_{\text{dyn}}$.

When significant decoupling occurs we neglect the thermal contribution to the collision frequency and write

$$\tau_{\text{coll}}^{-1} = (9 \times 10^{12} \text{ s}^{-1}) \frac{T_{\text{MeV}}} {s_5} \nu_{\text{rel}} Y_e \sigma_{10},$$

where $s_5 \equiv s/10^5$ and $\sigma_{10}$ is the neutron-proton cross section in units of $10^{25}$ cm$^2$. and $T_{\text{MeV}}$ is the temperature in MeV. As the precise energy dependence of $\sigma_{10}$ is not important here, it suffices to note a few representative values: $\sigma_{10}(\nu_{\text{rel}} = 0.1) = 17$, $\sigma_{10}(\nu_{\text{rel}} = 0.3) = 2$, and $\sigma_{10}(\nu_{\text{rel}} = 0.6) = 0.6$ [14].

The requirement of a non-negligible relative velocity then gives the decoupling time $t = t_{\text{dec}}$ as

$$t_{\text{dec}}/\tau_{\text{dyn}} = 4.6 + (1/3) \ln \left( \frac{\sigma_{10} \tau_{\text{dyn}} T_{0, \text{MeV}} Y_e} {s_5} \right).$$

In the above, $\tau_{\text{dyn}} \equiv \tau_{\text{dyn}}/10^{-6}$ s, and $\tau_{\text{coll}}$ was evaluated at a terminal velocity of 0.5. The calculated decoupling time is logarithmically sensitive to this choice. In reality the neutrons do not sharply decouple but continue to interact with the plasma over roughly a dynamical time scale. In this sense, the $t_{\text{dec}}$ appearing in Eq. (4) is an “effective” decoupling time. An accurate determination of $t_{\text{dec}}$ requires solving in detail the neutron and proton transport equations. However, because of the exponential decrease of density with time in the plasma frame, the number 4.6 appearing in Eq. (4) is only uncertain to approximately $\pm (1/3)$.

Once the neutrons decouple they will have an energy $Y_{\text{dec}}(1 - Y_e)M$. The ratio of kinetic energy in neutrons to the total energy in the fireball is then

$$f_n = (1 - Y_e) \frac{e^{t_{\text{dec}}/\tau_{\text{dyn}}}} {\eta} = 1.3(1 - Y_e) \left( \frac{Y_e \sigma_{10} \tau_{\text{dec}} - 6} {s_5^4} \right)^{1/3}.$$

(Here “total” energy includes both the thermal $e^+/\gamma$ energy and the bulk kinetic energy of baryons.) From this we see that for $Y_e$ less than

$$Y_{e,\text{crit}} \equiv 0.46 \left( \frac{s_5^4} {\sigma_{10} (1 \times 10^{-6})} \right)$$

at the time of decoupling the baryon loading problem is diminished. (Protons and neutrons each move with $Y_{\text{dec}}$ at the decoupling point; thereafter, protons will possess larger Lorentz factors than do average neutrons.) If the plasma remains optically thick to radiation until the energy in radiation is converted to kinetic energy of the remaining protons, energy conservation gives the final Lorentz factor of the protons

$$\gamma = \eta \frac{1 - f_n}{Y_e}.$$
in this way because the initial electron fraction depends in detail on the GRB central engine, whereas the later evolution of the fireball is generically given by the relations in Eq. (2). Many proposed GRB central engines involve neutrino heating or are site in environments subject to intense neutrino fluxes [12,15–22]. General discussions of the relation between neutrino processes and the dynamics of outflow may be found in Refs. [12,23–25]. However, the details of lepton decoupling are insensitive to how \( Y_e \) is set and we are not arguing for a specific GRB site.

The processes which have a significant effect on \( Y_e \) in the fireball environment are lepton capture/decay involving free nucleons and inelastic \( nn \rightarrow np \pi \) scattering (charged pion-nucleon bremsstrahlung),

\[
\begin{align}
\nu_e + n &\rightarrow p + e^-, \quad (8a) \\
\bar{\nu}_e + p &\rightarrow n + e^+, \quad (8b) \\
n &\rightarrow p + e^- + \nu_e, \quad (8c) \\
n + n &\rightarrow n + p + \pi^-.
\end{align}
\]

In general, \( Y_e \) is set by the competition between the above processes [1,26]. For the range of fireball parameters of interest to us, free neutron decay (8c) is unimportant as the fraction of neutrons decaying during the evolution of the fireball is \( \sim 10^{-9} \tau_{-6} \ln \eta \). Furthermore, as lepton capture is important only during the early, hot, evolution of the fireball and inelastic nucleon-nucleon scattering occurs only after neutron decoupling, the lepton capture and pion bremsstrahlung processes may be considered separately.

In environments where neutrino heating is important the forward reactions (8a) and (8b) can dominate in setting the electron fraction [1]. Integration of the rate equations corresponding to the lepton capture processes gives \( n/p = \lambda_{\nu_e,p}/\lambda_{\nu_e,n} = (L_{\nu_e} \langle E_{\nu_e} \rangle)/(L_{\bar{\nu}_e} \langle E_{\bar{\nu}_e} \rangle) \), where \( \lambda_{\nu_e,p} \) and \( \lambda_{\nu_e,n} \) are the rates for the reactions in Eqs. (8a) and (8b), \( \langle E_{\nu_e} \rangle \) and \( \langle E_{\bar{\nu}_e} \rangle \) are the average energies characterizing the energy spectra of the \( \bar{\nu}_e \) and \( \nu_e \) neutrinos, respectively, while \( L_{\nu_e} \) and \( L_{\bar{\nu}_e} \) are the corresponding energy luminosities.

Absent neutrino oscillations and flavor-type mixings, any thermal neutrino emission scenario from a compact object, will yield a characteristic average neutrino energy hierarchy for solar mass scale objects: \( \langle E_{\nu_e} \rangle = \langle E_{\bar{\nu}_e} \rangle = \langle E_{\nu_\mu} \rangle > \langle E_{\nu_\tau} \rangle > \langle E_{\nu_\nu} \rangle \). These considerations are consistent with findings in Ref. [12] in which a hard \( \bar{\nu}_e \) spectrum from a collapsing neutron star leads to an electron fraction in the fireball of \( Y_e \sim 0.1 \).

If the \( \nu_e \) component of the neutrino emission were to disappear or be greatly reduced, then the competition inherent in the above equations would be unbalanced in favor of the reaction \( \bar{\nu}_e + p \rightarrow n + e^+ \). This, in turn, would result in the wholesale production of neutrons. In fact, several schemes involving matter-enhanced active-sterile neutrino transformation have been proposed as a way of enabling \( r \)-process nucleosynthesis in neutrino-heated supernova ejecta: one of these involves matter-enhanced \( \nu_e \rightarrow \bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \nu_\tau \) [2]; the other involves matter-enhanced conversion \( \nu_\mu \rightarrow \nu_\tau \) followed by an active-active matter-enhanced conversion \( \nu_\mu \rightarrow \nu_\nu \) [3]. In either case, the initial \( \nu_e \) flux can be reduced by more than an order of magnitude and, in turn, this can translate into a substantial decrease in the initial \( Y_e \). (Just how low depends on central engine outflow hydrodynamics and on neutrino background effects [3,26–28].)

If we demand that an initially low \( Y_e \) not be raised above \( Y_e^{\text{crit}} \), consideration of lepton capture on neutrons allows us to place rough constraints on the fireball and neutrino parameters. We incorporate the uncertainty in the initial fireball evolution by supposing that the relations in Eq. (2) are valid only after the fireball has a Lorentz factor \( \gamma_i \) and temperature \( T_i \). Consideration of positron capture after \( \gamma = \gamma_i, T = T_i \) then leads to \( T_e < (22 \text{ MeV}) \times (Y_e^{\text{crit}}/\tau_{-6})^{1/3} \). Similarly, consideration of \( \nu_e \) capture on neutrons leads to \( T_e < (40 \text{ MeV}) \gamma_i (Y_e^{\text{crit}}/\tau_{-6})^{1/3} \). In deriving this limit above we have taken the \( \nu_e \) spectrum to be a Fermi-Dirac blackbody with temperature \( T_{\nu_e} \) and zero chemical potential. This limit could be modified or weakened if \( \nu_e \) flavor transformation occurs.

Determining the increase in \( Y_e \) due to pion production requires a proper treatment of neutron transport in the plasma. However, an upper limit on the increase is readily obtained by considering the extreme case where (i) the protons are frozen into the accelerating plasma, (ii) non-forward \( n-p \) collisions are assumed to result in maximal momentum exchange, (iii) \( n-n \) collisions are ignored except as a postprocessing step to determine \( \pi \) production, and (iv) the change in \( Y_e \) due to inelastic \( n-p \) and inelastic \( p-p \) scatterings is ignored. This simple picture gives an upper limit on the increase in \( Y_e \) because an exchange of any of the assumptions (i)–(iii) for more realistic ones has the effect of decreasing the velocity dispersion of the neutrons. By a calculation with the above assumptions we obtain the upper limit on the increase in \( Y_e \) to be \( \Delta Y_e \leq 10^{-3}/Y_{\epsilon_0} \), where \( Y_{\epsilon_0} \) is the initial electron fraction. Figure 2 displays the evolution of the neutron distribution function as
in the absence of boost. For a given energy input and baryon load, the dependence of the opacity on the Lorentz factor of the plasma may then be substantially increased from a factor of 2 to a factor of 5 as $\gamma$ increases from 0 to 1 (center of mass energy 2.08 GeV), reached at a relative velocity of 0.645 and even at a relative velocity (the product of cross section and relative velocity) of 0.728 (center of mass energy 2.08 GeV), for a wide range of fireball parameters. The final Lorentz factor of the plasma may then be substantially increased for a given energy input and baryon load.

Aside from the fireball energetics versus $Y_e$ issue addressed here, neutron-proton separation recently has been shown to have implications for the electromagnetic and high energy neutrino signatures of GRBs [13,29,30] and may well have implications for afterglow energetics. Large volume detectors such as AMANDA/ICECUBE and future experiments such as XENON will be able to provide high energy neutrino data on GRBs [31]. Perhaps the details of neutron decoupling and the associated electromagnetic/neutrino signature could allow a diagnostic of the weak interaction physics deep in GRB central engine environments.

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