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The Link Between Neutrons, the Weak Interaction, and the Gamma-Ray Burst Baryon-Loading Problem

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Abstract

Here we describe a surprising link between the weak-interaction and neutrino physics deep within the Gamma-Ray Burst (GRB) central engine and the acceleration of the fireball which produces the γ-rays. In particular, we discuss how the baryon loading problem in GRB fireballs depends on whether the baryons are neutrons or protons. It is found that a large neutron excess can result in a reduced transfer of energy from relativistic particles to baryons in the fireball. In turn, this implies that the final Lorentz factor of the fireball can be increased significantly for a given initial energy input. This raises the possibility that observed electromagnetic or neutrino signatures could give key clues into the weak-interaction history of fireballs which, in turn, could give unique insights into the nature of GRBs.

Introduction

In this poster 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 and how a simple mechanism can give rise to a substantial dispersion in the GRB proton component. We highlight our work in Refs. [1, 2] (copies should be available below). The baryon dynamics described here can have significant consequences for neutrino and photon signals from GRBs [3].

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 [4, 5, 6].

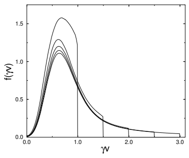
Inferences of the energetics and spectral observations of GRBs imply (i) total energies in gamma-rays approaching 10^{53} ergs for the most energetic events (in the absence of beaming), and (ii) large Lorentz factors of the progenitor fireball ($\gamma \sim 10^3$) (for a recent review, see Ref. [7]). 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 [8]. However, the relatively small cross sections characterizing the interactions of neutrons with the electron/positron/photon plasma may afford a solution to this problem.

A Simplistic Picture

This potential solution to baryon loading 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 $\sigma_{\rm T}$: neutron-electron (positron) scattering has $\sigma_{\rm ne} \sim 10^{-7}\sigma_{\rm T}$; and neutron-photon scattering has $\sigma_{\rm n\gamma} \sim 10^{-12}\sigma_{\rm T}$.

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 $Y_e = 1/({\rm n/p}+1)$.

FIG. 1: The Dynamic Fireball Neutron Distribution



The neutron distribution function $f(\gamma v)$ (normalized so that $\int f d(\gamma v) = 1$) at several time slices. The different time slices correspond to a plasma γv of 1, 1.5, 2, 2.5, 3, as measured in a frame comoving with the plasma near the decoupling point.

Neutron Decoupling

To go beyond the simplistic picture of non-interacting 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, γ_0 & Y_{e0}, respectively. Numerical and analytic work have shown the following simple scaling laws for such a configuration [8]:

$$\begin{aligned} &\text{For } R < \eta(R_0/\gamma_0) \Rightarrow \begin{cases} \gamma = \gamma_0\,(R/R_0) \\ T = T_0\,(R_0/R) \end{cases}, \\ &\text{For } R > \eta(R_0/\gamma_0) \Rightarrow \ \gamma = \eta. \end{aligned} \tag{1}$$

Neutron Coupling Interactions

The force that drags the neutrons along with the expanding plasma arises princiapally from n-p collisions. The relative contribution to the total force on the neutrons from collisions with electrons and positrons is roughly $F_{n-e}/F_{n-p} \sim m_e n_e \sigma_{ne}/m_p n_p \sigma_{np} \leq 10^{-10}\,(s/Y_e)$ and is small for the conditions we consider (s is the entropy-per-baryon). The neutron-photon cross section is small enough ($\sigma_{n-\gamma} \sim 10^{-36}[E_\gamma/(1\ {\rm MeV})]^2\ {\rm cm}^2$ where E_γ is the photon energy in the neutron rest frame) that n-γ interactions are negligible. If we denote by $\tau_{\rm coll}^{-1}$ the frequency of neutron/proton collisions (per neutron), we expect that the two components of the plasma will achieve a relative velocity given by $v_{\rm rel} \approx 2\tau_{\rm coll}/\tau_{\rm dyn}$ ($\tau_{\rm dyn}$ is the dynamical timescale; $c=1$). It is clear then that when $\tau_{\rm dyn} \gg \tau_{\rm coll}$ the neutrons are coupled to the rest of the plasma. However, decoupling occurs as these two timescales become comparable. Since the baryon number density in the plasma frame decreases as $e^{-3t/\tau_{\rm dyn}}$, decoupling will occur quickly, *i.e.* on a timescale shorter than $\tau_{\rm dyn}$.

Alleviation of Baryon Loading

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

$$f_n \approx (1-Y_e)\frac{e^{t_{\rm dec}/\tau_{\rm dyn}}}{\eta} \approx 1.3\,(1-Y_e)\left(\frac{Y_e\sigma_{10}\tau_{-6}}{s_5^4}\right)^{1/3}. \tag{2}$$

(Here "total" energy includes both the thermal $e^{\pm}/\gamma$ energy and the bulk kinetic energy of baryons. And, $t_{\rm dec}$ is the decoupling time; s_5 is the entropy-per-baryon in units of 10^5; σ_{10} is the neutron-proton cross-section in units of 10 fm; $\tau_{-6} \equiv \tau_{\rm dyn}/10^{-6}$ sec.)

Energy conservation gives the final Lorentz factor of the protons

$$\gamma \approx \eta\left(1 - \frac{f_n}{Y_e}\right). \tag{3}$$

For example, if $s_5 = 0.6, T_0 = 2\ {\rm MeV}$ (corresponding to $\eta \approx 100$), and $Y_{e0} = 0.02$, then the final Lorentz factor of the plasma after neutron decoupling (Eqs. (2), (3)) would be $\gamma \approx 1500$, which is 15 times larger than the standard case of $\gamma = \eta$. As another example, consider the Ref.[9] values of $\tau_{-6} = 27$ and $Y_e = 0.1$ and suppose that $T_0 = 10\,{\rm MeV}$ and $s_5 = 2.5$ (corresponding to $\eta = 2000$). In this case we find $\gamma = 1.1 \times 10^4$, an increase by a factor of 5.7. Clearly, the importance of this effect depends on how low Y_e can be.

Neutron Abundance & the Weak Interaction

Many proposed GRB central engines involve neutrino heating or are sited in environments subject to intense neutrino fluxes. General discussions of the relation between neutrino processes and the dynamics of outflow may be found in Refs. [9, 10, 11, 12]. However, the details of neutron 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 ${\rm nn} \rightarrow {\rm np}\pi$ scattering (charged pion-nucleon bremsstrahlung),

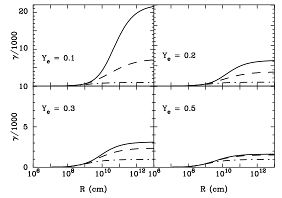
$$\nu_e + {\rm n} \rightleftharpoons {\rm p} + {\rm e}^- \tag{4}$$
$$\bar{\nu}_e + {\rm p} \rightleftharpoons {\rm n} + {\rm e}^+ \tag{5}$$
$${\rm n} \rightarrow {\rm p} + e^- + \bar{\nu}_e \tag{6}$$
$${\rm n} + {\rm n} \rightarrow {\rm n} + {\rm p} + \pi^-. \tag{7}$$

In general, Y_e is set by the competition between the above processes [4].

In environments where neutrino heating is important the forward reactions (4) and (5) can dominate in setting the electron fraction [4]. Considering the neutrino luminosity from collapsing stellar structures, one can show in general, low Y_e is likely [1], and is consistent with the findings in Ref. [9] in which a hard $\bar{\nu}_e$ spectrum from a collapsing neutron star leads to an electron fraction in the fireball of $Y_e \sim 0.1$.

Proton Dispersion

FIG. 2: Evolution of Lorentz Factor



Evolution of proton Lorentz factor in a steady state relativistic wind, for different cases of electron fraction, Y_e. The dot dashed is for when all baryons are assumed coupled to the plasma; the dashed line is for the case when neutrons are described by a distribution function and are allowed to decouple while protons are assumed "frozen" into the plasma; and the solid line the case when neutrons and protons both allowed to decouple.

A large dispersion in proton velocities can arise in GRB fireballs in which neutron decoupling occurs. Simple physical arguments and transport calculations indicate that the dispersion in Lorentz factor of the protons can be of order the final mean Lorentz factor of the fireball. Hence, this may provide the dispersion in proton Lorentz factors needed to give rise to the observed γ-ray emission, without recourse to multiple fireballs from the central engine [2]. There may be interesting consequences for the electromagnetic and neutrino signature of GRBs as well [3]. Future large volume high-energy neutrino detectors (AMANDA/ICECUBE) will be able to provide neutrino data on GRBs [13].

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