Heating and Deceleration of GRB Fireballs by Neutron Decay

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Abstract. Fireballs with high energy per baryon rest mass \( \eta > \eta_\ast \sim 400 \) contain a relatively slow neutron component. We show here that in this situation the thermal history of fireballs is very different from the standard adiabatic cooling.

INTRODUCTION

Baryonic matter ejected in a GRB explosion is partially composed of free neutrons (see [1] and [2] for detailed calculations and references). This has a strong impact on the external blast wave and changes the afterglow mechanism at radii \( r \lesssim 10^{17} \) cm [3]. We here investigate the dynamical effect of neutrons on the early evolution of a relativistic fireball, prior to the afterglow phase.

FIREBALL ACCELERATION AND NEUTRON-PROTON DECOUPLING

At the initial stage of the fireball acceleration, the neutrons are collisionally coupled to the protons and accelerated by radiation pressure at the same rate. If the energy-per-baryon, \( \eta \), is high enough, neutrons decouple before the acceleration stage is completed. This happens if

\[
\eta \geq \eta_\ast \simeq \begin{cases} 
400 \left[ \frac{L_{52}}{R_{07}^{1+\frac{1}{2}}} \right]^{1/4} & \xi \leq 1 \\
400 \left[ \frac{L_{52} \xi}{R_{07}^{1+\frac{1}{2}}} \right]^{1/4} & \xi > 1 
\end{cases}
\]

(1)

where \( \xi \) is the ratio of neutron and proton densities, \( R_0 = 10^7 \) cm \( R_{07} \) is the initial size of the fireball, and \( L = 10^{52} \) erg \( L_{52} \) is the equivalent isotropic luminosity of the explosion. Beyond the decoupling radius,

\[
R_{np} \simeq R_0 \eta_\ast \left( \frac{\eta_\ast}{\eta} \right)^{1/3},
\]

(2)

neutrons coast with a constant Lorentz factor.
\[\Gamma_n \simeq \frac{R_{np}}{R_0} \simeq \eta \left(\frac{\eta_r}{\eta}\right)^{1/3}.\]  

(3)

The optically thick proton fireball continues to accelerate as \(\Gamma_p \simeq r/R_0\) until the internal energy equals the proton rest-mass energy and acceleration is no longer efficient. If the fireball remains optically thick during the whole acceleration stage, its Lorentz factor saturates at

\[\Gamma_p \simeq \begin{cases} 
\eta & \eta < \eta_s, \\
\eta \left(1 + \xi - \frac{\xi}{\eta} \left(\frac{\eta_r}{\eta}\right)^{4/3}\right) & \eta > \eta_s, 
\end{cases}\]  

(4)

and the acceleration stage ends at radius

\[R_s \simeq \Gamma_p R_0.\]  

(5)

**ADIABATIC COOLING**

We first consider the thermal history of the fireball without neutrons. Electrons, protons, and radiation maintain a common temperature \(T\) in the early dense fireball via Coulomb collisions and Compton scattering, and \(T\) decreases adiabatically to very low values. During such adiabatic expansion, the photon-to-baryon ratio \(\phi = n_\gamma/n_b = \text{const} \sim 10^5\), and radiation completely dominates the internal energy and pressure. Therefore, \(T\) decreases according to the radiation adiabatic law with index \(\dot{\gamma} = \frac{4}{3}\). This continues until the fireball becomes transparent to radiation at the photosphere radius \(R_\tau\). Assuming \(R_\tau > R_s\), we have

\[R_\tau = \frac{L \sigma_T}{4\pi m_\gamma c^3 \Gamma_p^3},\]  

(6)

here \(\sigma_T\) is Thomson cross section. After becoming transparent the plasma is still tracking the temperature of the (freely streaming) photons, which is constant in the plasma frame if the fireball coasts with a constant Lorentz factor. The electrons decouple thermally from radiation only when the Compton timescale \(t_C = \Gamma_p (3m_e c/4 U_{rad} \sigma_T)\) where \(U_{rad}\) is the radiation energy density) exceeds the expansion timescale \(R/c\). This happens at radius

\[R_{e\gamma} = \frac{\sigma_T L}{3\pi m_e c^3 \Gamma_p^{7/3}} \left(\frac{R_0}{R_\tau}\right)^{2/3}.\]  

(7)

The protons decouple from the electrons when the Coulomb timescale \(t_{ep} \approx 17T^{3/2} n_e^{-1} \Gamma_p s\) exceeds \(R/c\). The corresponding radius of e-p decoupling is

\[R_{ep} \simeq (68\pi m_p c^4)^{-1} \frac{L}{\Gamma_p^3 T_s^{3/2}} \left(\frac{R_\tau}{R_s}\right),\]  

(8)
where \( T_s = T_0 / \Gamma_p \) is the temperature at the saturation radius, and \( T_0 \) is the initial temperature of the fireball. The protons decouple thermally from the electrons before the electrons decouple from radiation if \( R_{ep} < R_{e\gamma} \). One can show that \( R_{ep} / R_{e\gamma} \approx 4 \times 10^{-2} T_{s,7}^{-3/2} (R_{\tau}/R_s)^{5/3} \) (with \( T_s = T_{s,7} \times 10^7 \) K). At radii \( R > \min (R_{e\gamma}, R_{ep}) \), the protons are decoupled from radiation and cool adiabatically with index \( \hat{\gamma} = \frac{5}{3} \).

Thus, in the absence of neutrons, the fireball cools down adiabatically as \( T \propto r^{-1} \) during the acceleration stage and as \( T \propto r^{-2/3} \) during the subsequent coasting stage (\( \Gamma_p \sim \eta \)) up to the transparency radius. After thermal decoupling from radiation the protons cool as \( T_p \propto r^{-4/3} \). The thermal history of a pure proton fireball is shown by dot-dashed curve in Fig. 1. For most of the early evolution, the fireball is a cold coasting outflow. The presence of neutrons and their \( \beta \)-decay change this picture.

### HEATING BY PROTON–NEUTRON COLLISIONS

Protons in the fireball are continuously heated via proton-neutron collisions [4]. The collisional heating reaches its peak at \( R \approx R_{np} \); at \( R < R_{np} \) the n-p collisions are frequent but the relative velocity of the neutron and proton components is small (\( \beta_{np} \approx t_{np} R_{np} / c < 1 \)) and at \( R > R_{np} \) the relative velocity is relativistic \( \beta_{np} \sim 1 \) however the collisions are rare. The collisional heating, thus, peaks at \( R_{np} \) where the relative velocity becomes comparable to the speed of light and the rate of collisions still allows an efficient transfer of energy on a dynamical timescale. There are two sinks of heat gained by protons via n-p collisions: adiabatic cooling and Coulomb scattering off electrons. The competition between heating and cooling shapes the first peak in the proton temperature profile (Fig. 1). At \( R = R_{ep} \) the energy transfer from the protons to the electrons becomes inefficient on the expansion timescale \( R/c \). Then most of the heat gain by protons remains stored in the proton component, not given to the electrons and radiation.

### FIREBALL HEATING AND DECELERATION BY DECAYED NEUTRONS

In a fireball with \( \eta > \eta_* \), the neutrons have a smaller momentum than the protons after \( R_{np} \). Their decay products \( e^- \) and \( p \) exchange momentum with the ion fireball and heat it up. The heating of an ion medium by \( \beta \)-decay of neutrons moving with respect to the medium was discussed in [3]. The decay particles exchange momentum with the medium through the two-stream instability or because of gyration in a transverse magnetic field frozen into the medium. Since the neutrons decay gradually at all radii, this momentum exchange and heating take place continuously from the moment of decoupling.

The heating rate of the fireball due to \( \beta \)-decay is

\[
\frac{dE_h}{dr} = (\Gamma_{rel} - 1) \frac{dM_{np}c^2}{dr},
\]  

(9)
where $\Gamma_{\text{rel}}$ is the neutron Lorentz factor in the fireball rest frame,

$$\frac{dM_{np}}{dr} = \frac{M_n}{R_\beta},$$

(10)

is the decayed neutron mass per unit radius, and

$$R_\beta \simeq 0.8 \times 10^{16} \text{ cm} \left(\frac{\Gamma_n}{300}\right)$$

(11)

is the mean radius of decay. The heating by $\beta$-decay begins at $R_{np}$ and significantly changes the thermal history of the fireball. It shapes the second peak in proton temperature (see Fig. [I]).

As long as proton thermal energy is much below $m_p c^2$, adiabatic cooling is small compared to heating and the proton temperature increases linearly with radius,

$$T_p \propto r.$$

At a radius $R_{dis}$ the dissipated bulk kinetic energy equals the total energy of the fireball and $\Gamma_p$ begins to decrease. Between $R_{dis}$ and $R_\beta$ the $\beta$-decay heating balances the adiabatic cooling and

$$\Gamma_p \propto \left(\frac{R_\beta}{r}\right)^{1/2}.$$

When the fireball reaches $R_\beta$ the neutron component is exponentially depleted and the dissipation process switches off. The adiabatic cooling then leads to a power-law decrease in temperature,

$$T_p \propto r^{-4/3}.$$

**DISCUSSION**

We have shown here that the presence of a neutron component greatly affects the early dynamics of GRB fireballs with $\eta > \eta_* \sim 400$. Contrary to the pure proton model, the fireball with a neutron component heats up significantly at $R \gtrsim R_{np}$. In a popular GRB scenario, the bulk energy is partially converted into the observed $\gamma$-rays through shock waves inside the fireball at $r \gtrsim 10^{12} \text{ cm}$ [5]. The $\beta$-decay process described here should affect the internal shocks. It decelerates the fastest portions of the inhomogeneous fireball and reduces the contrast of Lorentz factors, which should significantly reduce the dissipation efficiency of internal shocks. A detailed study of these effects is in preparation.

**REFERENCES**

1. Derishev, E. V., Kocharovsky, V. V., and Kocharovsky, V. V., ApJ, 521, 640–649 (1999).
FIGURE 1. Proton temperature as a function of radius in a fireball with neutron-to-proton ratio $\xi = 1$ (solid curve). The relevant radii $R_{sp}$, $R_{np}$, $R_\tau$, $R_s$, and $R_\beta$ are shown by vertical dashed lines (note that $R_s = R_\tau$ in this case). For comparison, the dot–dashed curve shows the evolution of a pure proton fireball ($\xi = 0$) with the same luminosity $L = 10^{52}$ erg s$^{-1}$, initial radius $R_0 = 10^7$ cm and final Lorentz factor $\Gamma_p \approx 1040$.

FIGURE 2. The bulk Lorentz factor of protons (solid line) and neutrons (dot-dashed line) as a function of radius for the same parameters as in Fig. 1.

2. Beloborodov, A. M., ApJ, 588, 931–944 (2003).
3. Beloborodov, A. M., ApJ, 585, L19–L22 (2003).
4. Pruet, J., Abazajian, K., and Fuller, G. M., Phys. Rev., 64, 63002–+ (2001).
5. Rees, M. J., and Mészáros, P., ApJ, 430, L93–L96 (1994).