GRBs as Neutron-loaded Outflows

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Recent studies show that gamma-ray burst (GRB) engines are neutron rich site. In any model, an outflow would be produced and powered by accretion onto a few solar mass black hole. The temperature and density conditions of the disk, within tenths of Schwarzschild radii, allow for a dominant presence of free baryons, with a neutron eccess ($Y_e < 0.5$). The outflow matter content is directly picked up from this neutron-rich inner part of the disk. Since the escape (viscous) time-scale is shorter than the de-neutralization time-scale, the initial nuclear composition of the ejecta mirrors that of the disk. Therefore, GRBs are neutron-loaded outflows. Subsequent nucleosynthesis does not alter the neutron over proton ratio. Two questions come then natural: how do neutrons affect the evolution of the outflow? How does this evolution compare with the standard neutron-free theory? In this work, we address these issues, calculating consistently the dynamics and thermodynamics of a neutron-loaded fireball. We show that its thermal hystory is very different from the standard adiabatic cooling evolution and that the flow can be decelerated by the dissipative process triggered by the neutron β-decay.

1. Introduction

Any current model for Gamma-Ray-Burst engines involves the formation of a hyper-accreting ($\dot{M} \sim 1 M_\odot$) disk of few $M_\odot$ around a newly born black hole of comparable mass.

This scenario is advocated both for long and short bursts. In particular, long GRBs are thought to be associated with the final catastrophic stages of the death of a massive star [1]. While switching off, the very inner core of this star would collapse into a black hole that starts attracting and swallowing the rest of the star: this spirally inflow of mass forms an accretion disk. Before falling into the black hole, part of the accreted matter would be expelled perpendicularly to the disk in the form of two symmetric and highly relativistic jets. For short bursts, the accretion disk and the black hole would be formed after the merging of two compact objects, e.g. two neutron stars [2].

It is thus possible to study the nuclear composition of the accretion disk that powers a GRB jet, regardless how it was formed in first place [3]. In the innermost part of the disk, the temperature and density are such that all heavy nuclei are photo-disintegrated into free baryons and that neutrons outnumber protons. Since the jet matter content is directly and extremely rapidly picked up from these inner-disk regions, it initially mirrors the nuclear composition of the disk. As the neutron-rich material is ejected into an expanding outflow, the neutrons tend to recombine with the protons to α-particles, however, this recombination is only partially successful [3–5] . Even in the extreme case of complete recombination, a significant neutron component survives because the baryonic material has a neutron excess, while the formation of α-particles consumes equal numbers of neutrons and protons. The abundance of leftover neutrons in the relativistic outflow can vary from 10% to more than 90% depending on the precise parameters of the outflow.

These recent results put into question the applicability of the standard model for a GRB fireball [7], where baryonic matter is composed by protons only.

Our goal is to compute, for the first time, the dynamical and thermodynamical evolution of such neutron-loaded relativistic explosion, neglecting any interaction with the matter surrounding the star. We focus on the simple hydrodynamic picture of a matter-dominated outflow driven by thermal pressure; we also neglect possible dynamical effects of magnetic fields. The model is further simplified by the assumption that the outflow is adiabatic, i.e., its radiative losses are small compared to its total energy.

This study is meant to be a starting point for more complicated investigation, where our assumptions could be relaxed and more ingredients, like the presence of magnetic energy, could be considered.

2. The standard neutron-free model

In the standard model, most of the energy of the outflow is, initially, in form of thermal radiation. This "fireball" is polluted by protons at rest with a total mass of $\sim 10^{-4,-5} M_\odot$. Since the ratio between internal energy and rest-mass energy is greater than 100, the fireball is bound to explode. Radiation pressure accelerates protons ($\Gamma \sim r$) and eventually ($R \sim R_s$) most of the total energy is in ultra–relativistic ($\Gamma > 100$) protons that start coasting with constant speed (see Fig.1, upper panel). Parallely, there are two thermodynamical phases, and the transparency radius (R_τ), where matter becomes transparent for photon scattering, marks the transition. For $r < R_\tau$, all the components of the fireball acts as a relativistic fluid that undertakes adiabatic expansion. There is a single temperature that decreases as

$$T_r = T_0 \left(\frac{n}{n_0}\right)^{1/3}, \tag{1}$$

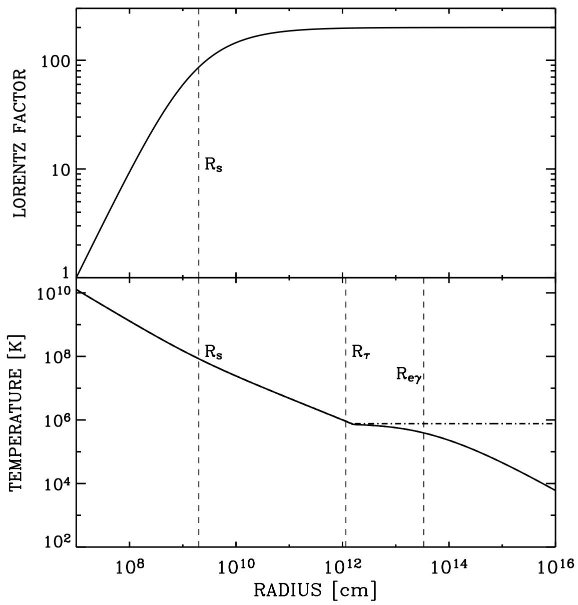

Figure 1: Lorentz factor (upper panel) and temperature (lower panel) as functions of radius for a neutron-free outflow with $L = 10^{52}$ erg/s, $\eta = 200$ and $R_0 = 10^7$ cm. Electrons never decouple thermally from protons and their common temperature is shown by the solid curve. Dashed-dotted curve shows the radiation temperature.

where $n = \rho_p/m_p$ is the baryon number density; T_0 and n_0 are the initial values at the initial radius $r = R_0$. After becoming transparent the plasma is still tracking the temperature of (freely streaming) photons: $T_e \approx T_p \approx T_r \approx const$ until the electrons decouple either from radiation (e-γ decoupling) or from the protons (e-p decoupling). The e-γ decoupling occurs at a radius $R_{e\gamma}$ where the Compton time-scale exceeds the expansion time-scale $\tau_{exp} = R/\Gamma_p\, c$. The e-p decoupling may happen or not depending mostly on the value of η. In Fig. 1 it is illustrated the case in which electrons and protons are still coupled at $R_{e\gamma}$ ($\tau_{ep} < \tau_{exp}$, where τ_{ep} is the Coulomb scattering timescale) and begin a common adiabatic cooling, $T_p = T_e \propto n_e^{2/3}$. They will not decouple later because $t_{ep} = const$ while τ_{exp} keeps increasing. This regime takes place at modest $\eta \lesssim 650$.

In summary, a proton fireball is for most of the time a coasting, adiabatic cooling outflow. The presence of neutrons will change this picture.

3. Neutron-loaded outflows

In order to calculate the dynamics of a neutron-loaded fireball, we now consider a four-component system, where radiation, electrons, protons and neutrons exchange energy and momentum. The baryonic content changes with radius. The initial neutron over proton ratio $\xi = \xi_0$ evolves with radius because neutrons continuously β-decay into protons,

$$n \to p + e + \bar{\nu}.$$

The mean life-time of neutrons in their rest frame is $\tau_\beta \approx 900$ s, and the corresponding mean radius of β-decay is

$$R_\beta = \int_0^{\tau_\beta} c\beta_n\Gamma_n\, d\tau \simeq 8\times10^{15}\left(\frac{\Gamma_{nf}}{300}\right)\ \mathrm{cm}, \qquad (2)$$

where Γ_n is the neutron Lorentz factor and $\beta_n \approx 1$; Γ_{nf} is the final value of Γ_n achieved at $r \sim 10^2 R_0 \ll R_\beta$. The neutron population is gradually depleted and the n/p ratio evolves with radius as

$$\xi = \frac{\xi_0 e^{-r/R_\beta}}{1+\xi_0\left(1-e^{-r/R_\beta}\right)}. \qquad (3)$$

With respect to the standard case, two new physical processes should be now taken into account: strong collisions between baryons and plasma instabilities triggered by neutron β-decay. Both dissipative mechanism convert the proton kinetic energy into thermal motion; the mean dissipated energy per baryon is the mean relative kinetic energy $(\Gamma_{\rm rel}-1)m_p c^2$ between neutrons and protons. On the one hand, radiation accelerates protons via electrons; thus, protons acquire a relative velocity that is effectively dissipated by collisions (which randomize the ordered momentum) as long as the collisional time-scale is shorter than the proton acceleration time-scale. On the other, the β-decay process continuously injects slow protons ($\Gamma \sim \Gamma_n$) into a background plasma of "original" fast protons. The difference in kinetic energy is quickly redistributed (on a time-scale given by the plasma frequency $\sim \omega_p^{-1}$). Conservation laws give us the final speed of protons. As a matter of fact, this mechanism can effectively slow down the proton flow, while the dissipated energy goes into thermal energy.

The quantitative results (assuming steady state) are obtained through:

- the conservation of energy,

$$L = 4\pi r^2 c\left[\beta_p\Gamma_p^2\left(\frac{4}{3}a\,T_r^4+\rho_p\,c^2\right)+\beta_n\Gamma_n^2\rho_n c^2\right] = const, \qquad (4)$$

  where ρ_n and ρ_p are respectively the proper density of the neutron and the proton component; the thermal energy of the plasma and neutrons has been neglected compared to their rest-mass energy.

- the conservation of baryons,

$$\dot{M} = 4\,\pi\,r^2\,c\,(\beta_p\Gamma_p\rho_p+\beta_n\Gamma_n\rho_n) = const, \qquad (5)$$

  where $\beta_p \approx 1$ and $\beta_n \approx 1$.

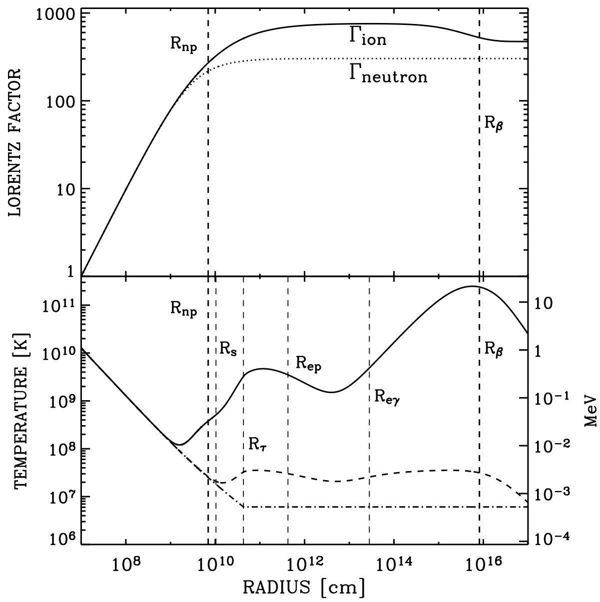

Figure 2: *upper panel*: proton (black line) and neutron (blue line) Lorentz factors; *bottom panel*: proton (black line), electron (red line) and radiation (blue line) temperature. All quantities are functions of the fireball radius and calculated for a neutron rich wind with $\xi = 1$, $L = 10^{52}$ erg/s, $\eta = 520$ and $R_0 = 10^7$ cm.

- the conservation of internal energy,

$$d\left(\frac{3}{2}\frac{n_i kT_i}{n}\right) = dq_i - n_i kT_i d\left(\frac{1}{n}\right), \qquad i = e, p. \quad (6)$$

  for electrons and protons, where the volume heat change dq includes the detailed description of the energy exchange between particles. Radiation temperature, instead, obeys again the adiabatic law (Eq. 1) up to R_τ; after, it remains constant.

The results of our calculations are presented in Fig.2 and described in the following.

4. Results

At the initial stage of the fireball acceleration, neutrons are collisionally coupled to protons, thus radiation "pushes" protons, that, in turn, drag neutrons and all the baryons gain speed at the same rate. However, as the outflow expands, the density drops and collisions become too rare for the acceleration to be effective. Eventually (at $r \sim R_{np}$ in Fig. 2), neutrons start coasting with a constant Lorentz factor. Proton-neutron collision is not only a way to exchange momentum but also thermal energy: protons in the fireball are continuously heated via collisions with neutrons. There are two sinks for the heat gained by protons via neutron collisions: adiabatic cooling and Coulomb scattering off electrons. The first is due to the work done by the fireball while expanding. The second is the result of the Coulomb interaction of protons with electrons with much lower temperature.

While the adiabatic cooling is negligible for $r \gtrsim R_{np}$, the competition between heating and Coulomb cooling shapes the first peak in the proton temperature profile (Fig. 2, lower panel). At $R = R_{ep}$ the energy transfer from the protons to the electrons becomes inefficient (electron-proton collisions become to rare) and most of the heat remains stored in the proton component. When most of the radiation energy has been passed to protons (at $R > R_s$), the fireball is composed mainly by ultra-relativistic baryons moving at a constant speed: a faster proton component and a slower neutron component. Even if the two streams are part of the same outgoing jet, they do not interact directly by collisions. However, during the jet expansion, there is a stream of slow neutrons that continuously convert (by β-decay) into slow protons. The net result is that the fast flow of protons is slowed down by colliding with these "obstacles" found along the way. Again, the dissipated bulk energy is converted into thermal energy and protons are heated up: this causes the second dissipation peak in the proton temperature profile.

5. Discussion

The above picture underlines strong dissimilarities between a GRB explosion with or without neutrons. Contrary to the pure proton model, the fireball with a neutron component heats up significantly at $R > R_{np}$ and decelerate for $R \simeq R_\beta$. The condition in the fireball, where the prompt γ-ray radiation is produced, are thus different from those considered so far. In a popular GRB scenario, the bulk energy is partially converted into the observed $\gamma-$rays through shock waves inside the fireball at $r \gtrsim 10^{12}$ cm [9] . The β-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, when collisions take place. This should significantly reduce the strength of the shock wave that develops. Consequently, there should be a decrease in the internal-shock efficiency to convert relative kinetic energy into radiation. Since we observe a huge amount of energy released by a GRB explosion, it would be very unlikely that a highly inefficient mechanism, like internal shocks in a neutron rich flow, could account for the detected emission. This would urgently call for new models to explain the burst of γ-rays. Finally, this work can be extended to the case in which part of the initial internal energy is in form of magnetic field. The presence of a dynamically important magnetic field would lead to a larger relative final kinetic energy between neutrons and protons [8]. Thus the consequences of the dissipation processes described here would be even more spectacular: protons could reach easily a mild-relativistic temperature and a decrease of more than a factor of 10 of their initial Lorentz factor. This would definitely suppress internal shocks for most initial conditions of inhomogeneity for the flow.

Acknowledgments

References

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