Bursts from internal shocks: is it really synchrotron emission?

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Abstract. Within the standard internal shock scenario, synchrotron emission would produce a spectrum with slope $F_\nu \propto \nu^{-1/2}$, as immediate consequence of the cooling timescale being shorter than the integration time. This is in disagreement with the harder observed spectra, indicating that a different mechanism is responsible for the burst emission. Furthermore in this scenario pair production is expected when photons produced by inverse Compton emission are taken into account.

1. Introduction

As amply discussed during this meeting, within the standard scenario dissipation of bulk kinetic energy occurs at internal shocks, generated by e.g. the non-uniform emission from the central source, and subsequently at the shock formed when the fireball impinges onto the external medium. These dissipation events are observationally identified with the burst and the following afterglow radiation, respectively.

It is also quite generally accepted (see however Thompson 1994; Liang 1997; Ghisellini & Celotti 1999 and these proc.; Stern, these proc.) that the radiation is produced through synchrotron emission, although quantitative (and rather detailed) comparison of spectral and time evolution has been possible only for the afterglow phase (e.g. Sari, these proc.). For the burst itself, the observational support is quite weak except for the prediction of a typical energy of ~ few hundred keV, which seems indeed to characterize the GRB peak emission.

In what follows we point out that adopting the parameters of the internal shock scenario to interpret the GRB emission itself leads to: a) a clear discrepancy between the predicted and observed spectra; b) copious pair production.

1.1. The standard scenario

The complex variability patterns typical of GRB are attributed to the emission from “shells” of matter ejected from the central engine, e.g. with different Lorentz factors, interacting. The faster shell would reach the slower one at typically $R_i \sim R_o \Gamma^2$, forming a shock, where bulk energy would be dissipated through acceleration of protons, electrons and amplification of magnetic fields.
In particular, it is assumed that electrons are energized instantaneously to a typical Lorentz factor which corresponds to equipartition with the other forms of energy: $\gamma_{eq} \simeq \epsilon_e (m_p/m_e)(n_p/n_e)$, where $n_p$ and $n_e$ are the densities of proton and electrons and it is assumed that $n_p = n_e$, i.e. there is not a significant amount of electron–positron pairs. These electrons would then radiate through synchrotron. Whether the magnetic field transports a significant fraction of the total power as Poynting flux or shares a fraction $\epsilon_B$ of the energy which is randomized in the internal shock, its estimated value is $B \simeq (2\epsilon_B/cL_s)^{1/2} \Gamma^{-1} R^{-1}$, where $L_s$ is the synchrotron radiated luminosity.

Thus the typical burst peak frequency is predicted to be

$$\nu_s \sim 2\epsilon_B^{1/2} \epsilon_e^{1/2} L_s, 48 R_{\odot}^{-1} \Gamma^{-2} (1 + z)^{-1} \text{MeV} \tag{1}$$

in good agreement with observations. This constitutes one of the most robust supports to the standard scenario accounting for the burst emission. This agreement nevertheless requires that both field and electron energies are close to equipartition (i.e. $\epsilon_B \sim \epsilon_e \sim 1$) and that $\Gamma$ is constrained within a tight range of values.

2. The predicted (integrated) spectrum

The main point we want to stress here is that the particle cooling timescales are much shorter than the integration timescale, and as a direct consequence, the predicted synchrotron spectrum in the entire X–ray band should have a slope $F_\nu \propto \nu^{-1/2}$, in clear conflict with observations.

In fact, the radiative timescale of an electron radiating via synchrotron (and self–Compton) in this scenario is:

$$t_{\text{cool}} \sim 10^{-7} \epsilon_e^3 \Gamma_2 \nu_{\text{MeV}}^{-2} (1 + U/e_B)^{-1} (1 + z)^{-1} \text{s} \tag{2}$$

which is always much smaller than the typical integration time (of the order of 1 s). Thus one always observe the emission by cooled particles. As the particle distribution at each time $N(\gamma, t) \propto \gamma^{-1}$ (to conserve the particle number), when integrated (i.e. weighted over the cooling timescale) gives $N(\gamma) \propto \gamma^{-2}$. The corresponding (observed) spectrum would then have a slope $F_\nu \propto \nu^{-1/2}$.

2.1. Possible alternatives?

The above result seems inevitable within the specific assumptions of the equipartition synchrotron scenario. Let us consider alternative hypothesis which would allow to avoid the above conclusion. The simplest possibility is to envisage a situation where energy equipartition is not reached and $\epsilon_B$ and/or $\epsilon_e$ are $\ll 1$.

However, the following considerations apply:

- in either cases (i.e. $\epsilon_B$ or $\epsilon_e$ $\ll 1$) both parameters have to be orders of magnitudes smaller than the equipartition value in order for $t_{\text{cool}}$ to be

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1 $\epsilon_B$ and $\epsilon_e$ have been estimated only by applying the synchrotron scenario to the afterglow/external shock phase.
comparable to the integration time. No typical peak energy for the burst would then be expected;

- if $\epsilon_B \ll 1$, although the synchrotron cooling would be slower, the amount of radiation energy density in the emitting region - which necessarily corresponds to the observed fluxes ($U_{\text{rad}} \sim L_s/(4\pi c R^2 \Gamma^2)$) - implies that the inverse Compton cooling timescale would be much shorter than the integration time, leading again to a steep spectrum;

- a similar effect (i.e. increase of synchrotron cooling timescale but decrease in the inverse Compton one) would occur if the (strong) equipartition field was limited to a thin spatial region, so that electrons would not loose more than a small fraction of their energy before escaping it;

- $\epsilon_e \ll 1$ would lead to a very inefficient radiative dissipation, as the energy dissipated in the shocks is already assumed to accelerate all of the available particles;

- electrons could be continuously re-heated, thus avoiding the formation of a cooled particle distribution. As it is not possible to re-accelerate the very same particles (as this would exceed the total energetics), one has to assume that only ‘selected’ electrons are continuously accelerated for the entire duration of the shell–shell interaction. A strong fine tuning is then required, as both their number ($\sim$ total number of particles times the cooling time), and their energy ($\sim \gamma_{\text{eq}}$ although equipartition would not be reached) would be determined;

- even for a power law distribution of particles $\propto \gamma^{-p}$, resulting from continuous heating and cooling, a spectrum steeper than $F_\nu \propto \nu^{-1/2}$ is implied, as only a very small fraction of particles can be accelerated to high energies.

We conclude that the time integrated spectrum predicted by the standard scenario is steeper than what observed.

3. Pair production

The second effect which significantly alters the spectral predictions of the standard scenario is pair production. In fact, within the equipartition hypothesis, the Compton parameter of the emitting zone, whose thickness is determined by the electron cooling length, is of the order of unity. This implies that an amount of luminosity comparable with the synchrotron one is dissipated through inverse Compton scattering. The Compton component is going to be peaked at a (comoving) energy $\nu_c \sim 90 c^{-1/2} \epsilon_B \epsilon_e^{4/3} L_s^{1/2} R_{o,7}^{-1} \Gamma_{2}^{-3}$ GeV. It is therefore crucial to estimate the possible role of photon–photon interactions leading to electron–positron pair production. The optical depth for this process is proportional to the compactness in target photons:

$$\ell \simeq 270 \frac{L_{48}}{\Gamma_2^2 R_{13}} \frac{\Delta R}{R}$$

(3)
where $\Delta R$ is the travel path and $1/\Gamma$ is the typical angle between the interacting photons. Then $\tau_{\gamma\gamma} \sim \ell/60$ for observed photon energies $h\nu \sim \Gamma m_e c^2$ (and depends on frequency as $\nu^\alpha$ for larger energies).

If we consider the region in front of the emitting shell $\Delta R \sim R$ and hence $\ell$ is large: all photons above threshold would be absorbed and produce pairs, which in turn radiate and give raise to a cascade. The qualitative results (for a stationary source) are that: a) $\gamma$-rays are reprocessed into lower energy photons, leading to a steeper spectrum; b) leptons are created in large number, implying that the average energy per particle has to decrease.

4. Conclusions

Within the frame of the internal shock scenario synchrotron (and inverse Compton) emission do not seem to reproduce the spectrum of the burst itself. This directly follows from the requirement of short cooling timescales intrinsic to this scenario. Furthermore contrary to its assumptions, pair production is expected to occur. Even the relaxation of the equipartition hypothesis does not simply allow to overcome the difficulties of the model. (For a more detailed analysis see Ghisellini, Celotti & Lazzati 1999, in prep.)

Alternative hypothesis on the dissipation/particle acceleration and/or radiation processes seem to be required. Comptonization by a quasi–thermal particle distribution appears to be a promising possibility (Thompson 1994; Ghisellini & Celotti 1999 and these proc.; Stern, these proc.).

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