What is the radiative process of the prompt phase of Gamma Ray Bursts?

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Abstract. Despite the dramatic improvement of our knowledge of the phenomenology of Gamma Ray Bursts, we still do not know several fundamental aspects of their physics. One of the puzzles concerns the nature of the radiative process originating the prompt phase radiation. Although the synchrotron process qualifies itself as a natural candidate, it faces severe problems, and many efforts have been done looking for alternatives. These, however, suffer from other problems, and there is no general consensus yet on a specific radiation mechanism.

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INTRODUCTION

The field of Gamma Ray Bursts (GRBs) was surrounded by many years by a sort of fascinating “aura”, being for so long a complete enigma. Recent years saw a dramatic improvement of our knowledge about them, especially about their phenomenology, thanks to the data gathered by the Compton Gamma Ray Observatory (CGRO) [5], BeppoSAX [6], HETE II [17], Swift [7] and now Fermi [2] satellites.

The theoretical work, especially in the 90’, set the stage for what is now considered a basic standard model to explain the bulk of what we see (for reviews see e.g. [27], [20], [29], [23], [21]).

According to this standard scenario, a colossal injection of energy in a small volume lasts for a short time. The gravitational energy of a solar mass is liberated in a few seconds, in a volume having a radius of a few Schwarzschild radii. Black–body temperatures above $10^{10}$ K are then reached, and electron–positron pairs are produced. The mixture of photons and matter – the fireball – expands due to its internal pressure accelerating the fireball to relativistic velocities. The Lorentz factor increases as $\Gamma \propto R$ ($R$ is the distance from the black hole) until almost all the internal energy is converted into bulk kinetic motion. A little “fossil” radiation remains, but it carries a small fraction of the initial energy. There is then the need to reconvert the kinetic energy back to radiation. The fact that the spikes of emission during the prompt phase do not lengthen with time suggests that these episodes occur at the same distance from the black hole. Inhomogeneities in the jet, with regions going at different $\Gamma$–factors, produce shocks internal to the relativistic flow. These shocks accelerates electrons and enhance magnetic fields.

Synchrotron radiation is then the natural candidate to explain the radiation of the prompt phase. But it faces a severe problem: if electrons produce $\sim$MeV synchrotron
FIGURE 1. The distributions of low energy spectral indices $\alpha$ (left) and peak energy $E_{\text{peak}}$ (right) of BATSE and Fermi/GBM bursts. The spectral index $\alpha$ is the photon spectral index of the spectrum below the peak energy $E_{\text{peak}}$. The vertical line (left panel) shows the cooling limit ($\alpha = -3/2$), while the dashed line shows the low energy synchrotron slope of a non-cooling electron population with a low energy cut-off ($\alpha = -2/3$). Adapted from [22].

Photons with a reasonable efficiency, they must inevitably cool in a time [13]:

$$t_{\text{cool}} = 10^{-7} \frac{\varepsilon_e^3 (\Gamma' - 1)^3 (\Gamma/100)}{v_{\text{MeV}}^2 (1 + U_t + U_B)(1 + z)} \text{ s}$$

where $U_t$ and $U_B$ are the radiation and magnetic energy densities, $\varepsilon_e$ is the fraction of the dissipated energy given to electrons, and $\Gamma'$ is the relative Lorentz factor between two colliding shells. This time is shorter than any conceivable dynamical time and of any detector exposure time.

The synchrotron spectrum of a cooling population of relativistic electrons cannot be harder than $F(\nu) \propto \nu^{-1/2}$, corresponding to a photon spectrum $\dot{N}(\nu) \propto \nu^{-3/2}$, while the vast majority of the observed spectra, below their peaks, is much harder, as illustrated by Fig. 1, showing BATSE (onboard CGRO) and the recent Fermi results [22]. This slope is substantially softer than the "synchrotron line of death" [24], $\dot{N}(\nu) \propto \nu^{-2/3}$, of a non-cooling electron population with a low energy cut-off.

SEEKING ALTERNATIVES

Re-acceleration – The first obvious possibility coming in mind is that the electrons are re-accelerated, so that they can remain at the same energy. In the internal shock scenario this is not possible, since electrons are kicked to high energies only once. Another critical problem is about the global energy budget. If I keep the radiating electrons hot
by refilling their energy, I can do so with a few (not all) electrons present. In standard conditions, I can do so only for one in a million electron.

**Jitter radiation** – Small scale changes in direction of the magnetic field can induce the so-called jitter radiation, similar but not identical to the synchrotron one. However, if the process is efficient, as it should be, the electrons cool, and the predicted spectrum is steep.

**Self Compton** – The cooling is very fast anyway [13], and the predicted first order self Compton spectrum is even steeper than the synchrotron one: $F_{SC}(\nu) \propto \nu^{-3/4}$ in the Thomson regime. If most of the scatterings occur in the Klein Nishina regime, then the electron distribution may flatten, and the synchrotron radiation is harder [3], but this necessarily implies that the self Compton process is dominating, in the GeV energy band and beyond. The few ($\lesssim 10\%$) GRBs detected by *Fermi* LAT at high energies then suggests that this process is not a general solution.

**External Compton** – The seeds for the Compton process can be “fossil” photons remaining from the acceleration phase, or any other radiation produced externally to the jet. But the electrons will cool also in this case, if the process is efficient, making a $\nu^{-1/2}$ spectrum.

**Quickly decaying magnetic fields** – Electrons quickly going away from the acceleration site could emit in a region of smaller magnetic field, then reducing their synchrotron losses (and power). The observed synchrotron spectrum is produced when the electrons are “young” and not cooled. However, once they are out of the magnetised region, they would inevitably and efficiently cool by self Compton, that is bound to become the dominant process, with a corresponding steep spectrum [13].

**Adiabatic losses** — The cooling time is much shorter than any conceivable dynamical time of the entire fireball. On the other hand, we could have many small regions expanding quickly enough to make electrons loose energy by adiabatic, not radiative, losses. This may also be accompanied by a decreased magnetic field. Needless to say, this process is by construction very inefficient.

**Quasi–thermal Comptonization** — Keeping the internal shock idea, but abandoning the requirement that the shock accelerates electrons only once, we can envisage a scenario were all electrons present in the emitting region (i.e. the shell) are maintained hot by some unspecified process [12]. The equilibrium between heating and cooling fixes the typical energy of these electrons. If the heating rate is simply the available dissipated energy divided by the interaction time between two shells, one arrives to typical electron energies that are sub–relativistic. The main radiative process in this case is quasi–thermal Comptonization, using as seed photons either the self absorbed synchrotron photons produced by the electrons themselves, or the “fossil” photons. The Comptonization parameter $\gamma$ becomes of the order of 10 or so, large enough to produce a hard spectrum. Expansion of the fireball during the Comptonization process may quench the process itself (expansion introduces a general radial motion for both photons and electrons; but see [19] for a non expanding case resulting from recollimation). Furthermore, the typical observed energy peak of the spectrum could be too high, if the electron “temperatures” in the comoving frame are above $\sim 10$ keV or so.
The above ideas have been proposed to occur within the internal shock scenario. In the following I will list more radical ideas, that no longer assume that the dissipation process is due to internal shocks.

**Bulk Compton** — The association of long GRBs with supernovae led us ([18], [14]) to propose an alternative scenario for the production of the prompt phase emission, namely to make use of the dense radiation field produced by the funnel or the progenitor star (that is about to explode) or by the young and hot remnants (if the supernova explosion precedes the GRB). The process can be very efficient, especially for large $\Gamma$–factors. There is no need of shocks and no need of a transfer of energy from protons to electrons. Being so efficient, it is conceivable that the fireball decelerates, leaving less energy to be dissipated during the afterglow. This would solve another puzzle concerning GRBs. One of the problems it faces is that the fireball has a large scattering optical depth, and so uses a large fraction (if not all) the seed photons. Furthermore, variability in this model should correspond to emission by different shells, but there is a minimum “refilling time” needed to replace the scattered seed photons with new ones. Also, the similarity of the spectra of long and short GRBs [10] (if short bursts are not associated to a supernova) makes the bulk Compton idea questionable.

**Deep impacts** — The initial fireball must punch a funnel through the progenitor star. If the opening angle of the jetted fireball is $\theta = 0.1 \sim 5^\circ$, then each one of the two oppositely directed fireballs must push a mass $M \sim 0.5(\theta / 0.1)^2(M_*/20 M_\odot)$ solar masses out of the progenitor star of mass $M_*$. Once the funnel is clean, the fireball may still interact with some material leftover from the previous (“piercing”) phase, at a distance of the same order of the star radius [15]. Moreover, shear instabilities between the fireball and its cocoon (while the fireball is moving inside the funnel) may give important dissipation [26], [19]. The efficiency can be large, especially when the fireball collides with leftover material just outside the star surface, because it is a collision with matter that is initially almost at rest. If these collisions occur when the scattering optical depths are large, then the predicted spectrum has time to thermalize, and then it is a black–body. Under the assumption of black–body spectrum and other specific conditions (even if they appear somewhat ad hoc), [26] showed that it is even possible to reproduce the “Amati” relation [1], namely the correlation between the observed energetics of the prompt radiation phase and the peak energy of the $\nu F_\nu$ spectrum of the total prompt emission.

The problem with these interesting attempts is the presence of a black–body component in the prompt phase spectrum. While some GRBs do have black–body like spectra up to a few seconds from the trigger [8], the vast majority do not. Fits with a back–body plus a power law can be successfully applied to many more bursts [25], but the resulting power law is rather soft. Therefore, even if in the BATSE energy range one obtains a good fit, the extrapolation of the power law component to lower frequencies results in a large flux. Larger than what observed when we do have lower frequency data, as was the case for the few GRB observed both by BATSE and by the Wide Field Camera (WFC) onboard *BeppoSAX* [9]. Moreover, for all those cases, a cut–off power law (without the black–body component) not only is a good fit in the BATSE energy range, but also its extrapolation to lower frequencies matches perfectly the WFC data.

**Reconnection** — The fireball could be magnetically dominated, dissipating part of
FIGURE 2. The left panel shows the Fermi/GBM light curve of GRB 090424. Vertical dashed lines indicate the time bins for which the spectrum was analysed. The right panel shows $E_{\text{peak}}$ vs luminosity for the different time bins. The solid and dashed dark lines indicate the slope and normalisation of the Yonetoku relation found considering different GRBs. Different symbols indicate the rising and decaying phases of the different pulses. Adapted from [10].

its magnetic energy through reconnection, as envisaged in [16]. If this kind of energy dissipation lasts for a relatively long time, then the electrons would be reaccelerated while cooling, and the dominant radiation process could be similar to the quasi–thermal Comptonization mechanism. The several spikes/pulses present in the light curve of the prompt emission phase should correspond to different reconnection events. This idea is attractive, and surely worth to be investigated further. The problem with it is that assuming dissipation events having different properties (i.e. energies, electron content, sizes, durations) would correspond to “Christmas tree” variations, namely each spike/pulse should behave independently from the others. There should be no well defined trends in the spectral properties of the prompt emission. Instead, these trends are present, and are rather strong. In fact, both [4] (for Swift bursts) and [10] (for Fermi/GBM bursts) found strong correlations between the peak energy $E_{\text{peak}}$ and the luminosity within the prompt emission of single bursts. Fig. 2 illustrates the point showing the $E_{\text{peak}}$–Luminosity correlation for GRB 090424. The slope and normalisation of these correlation is the same of what it is found considering different bursts, and taking for each of them the peak luminosity and the (time averaged) $E_{\text{peak}}$ (the so called Yonetoku correlation, see [28], and [10] for an update).

These trends give solidity and reality to spectral–energy correlations found in these years, demonstrating that they are not the result of selection effects.
CONCLUSION

We still do not know what is the dominant radiation process of the prompt phase emission.

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