Quasi–Thermal Comptonization and GRBs

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Abstract. Quasi–thermal Comptonization is an attractive alternative to the synchrotron process to explain the spectra of GRBs, even if we maintain other important properties of the internal shock scenario, implying a compact emitting region and an equipartition magnetic field. Photon–photon absorption and electron–positron pairs can play a crucial role: this process may lock the effective temperature in a narrow range and may be the reason why burst spectra have high energy cut–offs close to the rest mass–energy of the electron. If the progenitors of GRB are hypernovae, the circum–burst matter is dominated by the wind of the pre–hypernova star. The presence of this dense material has strong effects on the generation of the radiation of the burst and its afterglow.

1. Introduction

In Celotti & Ghisellini (this volume) we argue that interpreting the burst emission as synchrotron radiation faces some severe problems. This justifies the search for alternatives. Here we will argue that a valid alternative is quasi–thermal Comptonization. This has already been proposed to explain the burst emission by Liang (1997) and Liang et al. (1997), who required a relatively weakly magnetized (magnetic field $B \sim 0.1$ Gauss) and large ($R \sim 10^{15}$ cm) emitting region. These values of the physical parameters contrast with the ones advocated by the “standard internal shock” scenario as it has been developing to explain the structured GRB light curve and its fast variability, which requires a compact ($R \sim 10^{13}$ cm) and magnetized ($B \sim 10^5$ Gauss) emitting region (Rees & Mészáros 1992; Rees & Mészáros 1994; Sari & Piran 1997).

More recently, we (Ghisellini & Celotti 1999) have proposed again the quasi–thermal Comptonization scenario, but using the very same physical parameters as in the internal shock picture. The only (important) difference concerned the timescale of particle acceleration. Instead of considering it instantaneous, we considered that the particles can be re–accelerated for the entire duration of the shell–shell interaction, and therefore the acceleration timescale can last for $\Delta R'/c$, where $\Delta R'$ is the shell width as measured in the comoving frame.

In this case the typical electron energy is dictated by the balance between the heating and the cooling rate: assuming that the bulk Lorentz factor of one
shell in the comoving frame of the other is $\Gamma'$, we obtain:

$$\frac{(\Gamma' - 1)n'_p m_p c^2}{\Delta R'/c} = \frac{4}{3} n'_e \sigma T c (\gamma^2 - 1) U$$

(1)

where $n'_p$ and $n'_e$ are the comoving densities of protons and leptons, respectively, and $U$ is the total (radiative plus magnetic) energy density. The resulting particle distribution may well be different from a perfect Maxwellian, but it has in any case a narrow energy width, and a meaningful mean energy may be defined. It may also be possible that a high energy tail (possibly a steep power law) is present, producing a tail of high frequency radiation (see e.g. Stern 1999).

With such low values of the typical $\gamma$, the produced cyclo-synchrotron radiation is self-absorbed and the corresponding power is orders of magnitudes lower than the observed burst power and at much lower typical frequencies. This self absorbed radiation is nevertheless important, because it provides the seed photons to be scattered at high energies.

In this paper we will show why multiple Compton can provide typical spectral slopes in agreement with observations, and some ideas on how it is possible to have spectral cut-offs at the observed energies. Finally we will present some considerations on the hypernova scenario, based on the fact that the pre-hypernova star necessarily has a strong wind, which makes the the circum-burst surroundings very dense. The effects of this wind will be considered and discussed.

2. Quasi thermal–Comptonization

As mentioned above, the particle distribution may not be a perfect Maxwellian, but it can nevertheless have a well defined mean energy, which can correspond to an effective temperature. Let us then introduce a dimensionless effective temperature $\Theta' = kT'/(m_e c^2)$, measured in the comoving frame. Assume also that all particles in the shell, of optical depth $\tau' = \sigma T n'_e \Delta R'$, partecipate to the burst emission. The interaction between the shells is at a distance $R_i = 10^{13} R_{i,13}$ cm from the center, and the shell width is $\Delta R' \sim R/\Gamma$.

2.1. Seed photons

As long as the typical $\gamma$ factor of the emitting electron is low, the cyclo-synchrotron radiation is self absorbed, and the corresponding spectrum resembles a blackbody, peaking at the self-absorption frequency $\nu'_T$, which is a strong function of the temperature. Interpolating numerical results, Ghisellini & Celotti (1999) obtain $\nu'_T \sim 2.75 \times 10^{14}(\Theta')^{1.191}$ Hz, which holds for $0.1 \lesssim \Theta' \lesssim 3$. This gives, for $B \sim 10^5$ Gauss and $\tau_T \sim 1$, $\nu'_T \sim 2.75 \times 10^{14}(\Theta')^{1.191}$ Hz.

The corresponding comoving self-absorbed luminosity is

$$L'_s \sim \frac{8 \pi}{3} m_e R^2 \Theta' (\nu'_T)^3 \sim 7.6 \times 10^{41} \Theta' R_{i,13}^2 (\nu'_{T,14})^3 \text{ erg s}^{-1}$$

(2)

The same electrons will scatter these photons through multiple scatterings, in order to emit the burst luminosity. We can define a generalized Comptonization parameter as

$$y \equiv 4 \tau \Theta'(1 + \tau)(1 + 4 \Theta')$$

(3)
For values of $y$ larger than unity the final spectrum amplifies the synchrotron power by the factor $e^y$: values of $y$ around $10–13$ are needed to produce an intrinsic Compton power $L'_c \sim 10^{46}$ erg s$^{-1}$ starting from a synchrotron power $L'_s \sim 10^{41}$ erg s$^{-1}$.

### 2.2. A preferred slope: $\nu^0$

Thermal Comptonization has been extensively studied in the past years to explain the high energy spectra of galactic black hole candidates and radio–quiet AGNs (see e.g. Pozdnyakov, Sobol, & Sunyaev 1983). The fractional energy amplification of the scattered photons, at each scattering, is $A \sim 1 + 4\Theta' + 16(\Theta')^2$. When $\tau$ is significantly larger than unity, almost all photons undergo several scatterings, and in the Compton spectrum of each order we therefore have the same number of photons, of mean frequency $\nu_i$ and distributed in a range $\Delta \nu_i \sim \nu_i$ of frequencies. The escaping photons are a fraction $\sim 1/\tau$ of the ones contained in each spectrum. We therefore have that, in a $\nu-F_\nu$ plot, the spectrum of the escaping photons is flat ($F_\nu \propto \nu^0$) up to $\sim \Theta'$, where photons have the same energies of the leptons. At these energies a Wien peak forms ($F_\nu \propto \nu^3 \exp(-h\nu/kT')$), whose importance depends on the value of $\tau$ and $\Theta'$. In this case an increased (decreased) $\tau$ and/or $\Theta'$ make the Wien peak to become more (less) dominant, and at the same time they decrease (increase) the normalization of the power law part of the spectrum, but they do not change its slope.

### 2.3. Importance of pairs and feedbacks

The production of electron–positron pairs would surely be efficient for intrinsic compactnesses $\ell' > 1$, and would on one hand increase the optical depth, and on the other acts as a thermostat, by maintaining the temperature in a narrow range. Detailed time dependent studies of the optical depth and temperature evolution for a rapidly varying source have not yet been pursued. Results concerning a steady source in pair equilibrium indicate that for $\ell'$ between 10 and $10^3$ the maximum equilibrium temperature is of the order of $30–300$ keV (Svensson 1982, 1984), if the source is pair dominated (i.e. the density of pairs outnumbers the density of protons). Indeed we expect in this situation to be close to pair equilibrium, as this would be reached in about a dynamical timescale (i.e. in $\Delta R'/c$), but note that the quoted numbers refer to a perfect Maxwellian particle distribution. If an high energy tail is present, more photons are created above the threshold for photon–photon pair production with respect to the case of a pure Maxwellian, and thus pairs become important for values of $\Theta'$ lower than in the completely thermal case (see Stern 1999; Coppi 1999; Stern, this volume).

An ‘effective’ temperature of $kT' \sim 50$ keV ($\Theta' \sim 0.1$) and $\tau_T \sim 4$ dominated by pairs, can be a consistent solution giving $y \sim 11$. See also below for an effect which could considerably enhance the compactness of the emitting region, and therefore its pair density.

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1 We define the compactness as $\ell = \sigma_T L \Delta R'/(m_e c^3 R^2)$. See Celotti & Ghisellini, this volume, for more details.
3. The high energy cut–off

With $\Theta' \sim 0.1$, and $\Gamma \sim 100$, the observed high energy cutoff lies at $E_c \sim 10\Theta'_1 \Gamma_2/(1 + z)$ MeV. This value is somewhat larger than what is typically observed. However, there are a number of effects which may be potentially important, and that can lower this value. One is that the entire system is highly time–dependent, and the time–evolution is in the sense of a cooling of the leptons, which will then produce a time–averaged spectral energy cut–off lower than a few MeV. On the other hand, if the observed value of 300 keV is really typical, and not biased by selection effects introduced by triggering criteria and detector response energies (see e.g. Lloyd & Petrosian 1999, and Petrosian, this volume), we ought to look for a very robust explanation.

3.1. “Brainerd break”

Brainerd (1994) linked the typical high energy cut–off of GRBs to the effect of down–scattering: photons with energies much larger than $m_e c^2$ pass undisturbed through a scattering medium because of the reduction with energy of the Klein Nishina cross section, while photons with energies just below $m_e c^2$ interact, and their energy after the scattering is reduced. The net effect is to produce a “downscattering hole” in the spectrum, between $\sim m_e c^2/\tau^2$ and $\sim \tau m_e c^2$. The attractive feature of this model is that the cut–off energy is associated with the rest mass-energy of the electron. The difficulty is that a significant part of the power originally radiated by the burst goes into heating (by the Compton process) of the scattering electrons.

3.2. Pair production break

If some scatterings take place between the burst photons and some external medium at rest, there may be a very efficient process which modifies the emergent burst radiation, namely pair production. Assume in fact that the external medium has an optical depth $\tau_{\text{ext}}$ in a region close to where the burst radiation originates (i.e. between $R_i$ and $2R_i$). This material will scatter back a fraction $\tau_{\text{ext}}L$ of the burst power, corresponding to a compactness

$$\ell_{\text{ext}} \approx \frac{\sigma_T \tau_{\text{ext}} L}{R_i m_e c^3}$$  \hspace{1cm} (4)

If we require that the primary spectrum is not modified by photon–photon absorption, the optical depth of the scattering matter and its density must be

$$\tau_{\text{ext}} < 3.7 \times 10^{-9} \frac{R_{13}}{L_{50}} \Rightarrow n_{\text{ext}} < \frac{5.5 \times 10^2}{L_{50}} \text{ cm}^{-3}$$  \hspace{1cm} (5)

As can be seen, the requirement on the density of the external matter is particularly severe, especially in the case of bursts originating in dense stellar forming regions. On the other hand photon–photon opacity may be an important ingredient to shape the spectrum, and the reason why GRB spectra peak at around 300 keV. As in the Brainerd model, the attractive feature is to link the energy break to $m_e c^2$, while the difficulty is that all the primary radiation emitted above $m_e c^2$ get absorbed. Contrary to the Brainerd model, in this case the spectrum
does not retain its original slope above $\tau m_e c^2$, and implies that the GeV radiation observed by EGRET for some GBRs is produced in the afterglow. If the absorbed energy is not re-emitted, but remains in the form of lepton energy, this will significantly lower the efficiency of the burst to produce radiation. On the other hand it is conceivable to expect that the created pairs will radiate their energy in a short time, and that they can be even re-accelerated by the incoming fireball. The net effect may be simply to increase the density of the radiating particles, introducing a feedback process: an increased density lowers the effective temperature $\rightarrow$ less energy is radiated above $m_e c^2 \rightarrow$ the number of pairs produced via the “mirror” process decreases $\rightarrow$ the new pair density decreases, and so on. Another feedback is introduced by the fact that the photons scattered back to the emitting shell will increase the number of seed photons, softening the spectrum. All these effects deserve a more detailed investigation, even if their time-dependence nature will make these studies quite complex.

4. Pre-hypernova wind

If the progenitors of GRBs are hypernovae (Paczyński 1998), then we must consider the effects of the strong wind necessarily present during the pre-hypernovae phase. For illustration, assume a mass loss $\dot{m} = 10^{-4} \dot{m}_{-4} \dot{M}_\odot$ yr$^{-1}$ and a wind velocity $v = 10^8 v_8$ cm s$^{-1}$. The particle density $n_*$ near the surface of the pre-hypernova star of radius $R_*$ is

$$n_* = \frac{\dot{m}}{4\pi R_*^2 v m_p} = 3.15 \times 10^{12} \frac{\dot{m}_{-4}}{v_8 R_*^{12}} \text{ cm}^{-3} \quad (6)$$

and scales as $(R/R_*)^{-2}$. The mass contained in this wind decelerates the fireball at the deceleration radius $R_d$ where the wind mass equals the fireball mass divided by $\Gamma$

$$\frac{\dot{m}(R_d - R_*)}{v} = \frac{E}{\Gamma^2 c^2} \rightarrow R_d = R_* + \frac{E v}{\Gamma^2 \dot{m} c^2} = R_* + 1.75 \times 10^{13} \frac{v_8 E_{52}}{\Gamma^2 \dot{m}_{-4}} \text{ cm} \quad (7)$$

As can be seen, the deceleration radius is close to the transparency radius, i.e. the distance at which the fireball becomes transparent. The first immediate consequence is that internal shocks do not develop. The second immediate consequence is that the optical depth of wind material between $R_d$ and infinity is quite large

$$\tau_w(R_d - \infty) = \sigma_T \int_{R_d}^\infty n(R) dR \sim 0.2 \frac{\dot{m}_{-4}}{R_{d,13} v_8} \quad (8)$$

Due to the $R^{-2}$ dependence of the density, most of the contribution to this optical depth comes from material close to $R_d$. Therefore all the effects discussed above (downscattering and pair reprocessing) would take place.

The conclusion is that the hypernova hypothesis implies a scenario for the production of the burst and the afterglow quite different from the internal/external shock scenario. In this case in fact we have only external shocks between the fireball and a very dense medium. The fireball would decelerate
while producing the burst emission: if a significant fraction of the bulk energy ends up into radiation, this implies that the burst emission should contain more energy than the time–integrated afterglow emission. It may also imply a difference between the early and late burst emission, due to the fact that the corresponding emitting zones may have different $\Gamma$ factors. Since this is not observed (see e.g. Fenimore 1999, this volume), this may be a problem for the hypernova idea, but since processes different from collisionless shocks may be operating (instabilities, turbulences and so on), this issue is worth investigating.

From the point of view of the radiation processes, the pre–hypernova wind scenario offers an interesting possibility. At early times, the heating–cooling balance (Eq. 1) gives sub or trans–relativistic lepton energies. As the energy density $U$ decreases, the cooling becomes less rapid and lepton energies increase, becoming relativistic. Correspondingly, self–absorbed cyclo–synchrotron and multiple Compton may originate the burst emission, while the afterglow may correspond to synchrotron and self–Compton emission from relativistic electrons. Transition from these two regimes may be smooth. The self–absorbed cyclo–synchrotron radiation would increase its relative importance as the Lorentz factor of the emitting leptons increases, and develop a thin part when $\gamma$ becomes large enough (e.g. $\gamma > 100$), producing optical radiation. This may be an alternative explanation for the prompt optical flash of GRB990123. At later times, the particle energy may reach its maximum possible value (e.g. $\gamma = \Gamma m_p/m_e$), and then decrease following the usual prescriptions, with a power law time decay of the flux density.

5. Conclusions

If there is a balance between heating and cooling, the emitting leptons reach typical energies which are mildly relativistic at most. The most efficient radiation process in this case is quasi–thermal Comptonization of self–absorbed cyclo–synchrotron photons. This process is characterized, in the quasi–saturated regime, by a spectrum which maintains its flat slope (in the power law part) even if the emitting optical depth or the temperature change. What changes is the relative importance of the Wien peak. The emitting plasma may be dominated by the pairs produced through photon–photon interactions in the high energy part of the spectrum, and this may limit the effective temperature in a narrow range. Most important, in this respect, is the exact shape of the high energy part of the particle distribution, which may differ from a pure Maxwellian.

The observed high energy cut–off of the burst emission is well defined, and close to the rest–mass energy of the electron. This fact is difficult to be explained both by "standard" synchrotron models and by Comptonization models.

It calls for a more robust interpretation, where the energy $m_e c^2$ enters in a natural way. We have argued that photon–photon absorption may play again a crucial role if there is, in front of the fireball, some material scattering back a fraction of the burst radiation. This material may be the interstellar matter in a dense star forming region or the matter blown out from a pre–hypernova star. In the latter case the fireball is decelerated at typical distances $R \sim 10^{13}$ cm, i.e. where it has become transparent. There is no need to have internal shocks. Other problems however arises, still to be investigated.
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