ON THE ORIGIN OF GAMMA RAY BURST RADIATION

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In the standard internal shock model, the observed X and gamma–ray radiation is assumed to be produced by synchrotron emission. I will show that there are serious problems with this interpretation, calling for other radiation mechanisms, such as quasi–thermal Comptonization and/or Compton drag processes, or both. These new ideas can have important consequences on the more general internal shock scenario, and can be tested by future observations.

1 Introduction

The most popular interpretation of the origin of the $\gamma$–rays emitted during the prompt emission of Gamma–Ray Bursts (GRB) is synchrotron radiation, produced by relativistic leptons accelerated in shocks formed during the collisions of an inhomogenous fireball wind (the so called internal shock scenario, Rees & Mészáros 1992, 1994; Sari & Piran 1997).

The main evidence for the synchrotron origin of the prompt radiation is the successful prediction of the typical energy at which the observed spectrum peaks, in a $\nu F_\nu$ representation. However, the very same synchrotron shock scenario inevitably predicts very fast radiative cooling of the emitting particles, with a resulting severe disagreement between the predicted and the observed spectrum (Ghisellini, Celotti & Lazzati 2000, see also Cohen et al. 1997; Sari, Piran & Narayan 1998; Chiang 1999).

A further general problem of the internal shock scenario is its low efficiency in transforming bulk kinetic into random energy and then radiation (Kumar 1999; Lazzati, Ghisellini & Celotti 2000; Spada, Panaitescu & Mészáros 2000). External shocks (i.e. deceleration of the fireball by the circumburst matter) should be much more efficient. Since external shocks are associated with afterglow emission, it is strange that they are much less energetic than the prompt emission. It is then compelling to explore alternative possibilities.

2 A synchrotron origin?

2.1 Typical synchrotron frequency

Assume that two shells with slightly different velocities collide at some distance $R$ from the explosion site. In the comoving frame of the faster shell,
protons of the other shell have an energy density \( U'_p = (\Gamma' - 1)n'_p m_p c^2 \), where \( \Gamma' \sim 2 \) is the bulk Lorentz factor of the slower shell measured in the rest frame of the other, and \( n_p \) is the comoving proton density. The magnetic energy density \( U'_B \) can be amplified to values close to equipartition with the proton energy density, \( U'_B = \epsilon_B U'_p \). The proton density can be estimated by the kinetic power carried by the shell: \( L_s = 4\pi R^2 \Gamma^2 c n'_p m_p c^2 \), yielding \( B = (2\epsilon_B L_s/c)^{1/2}/(R\Gamma) \). Also each electron can share a fraction of the available energy, and if there is one electron for each proton, namely if electron–positron pairs are not important, then \( \gamma m_e c^2 = \epsilon_e m_p c^2 \). These simple hypotheses lead to a predicted observed synchrotron frequency

\[
h\nu_s \sim 4\epsilon_e^2 \epsilon_B^{1/2} \frac{L_{s,52}^{1/2}}{R_{13}(1+z)} \text{MeV}
\]

in very good agreement with observations. Note that the ‘equipartition coefficients’, \( \epsilon_B \) and \( \epsilon_e \), must be close to unity for the observed value of \( \nu_{\text{peak}} \) to be recovered. In turn this also implies/requires that pairs cannot significantly contribute to the lepton density.

2.2 Cooling is fast

The synchrotron process is a very efficient radiation process. With the strong magnetic fields required to produce the observed \( \gamma \)-rays, the synchrotron cooling time is therefore very short. As pointed out by Ghisellini, Celotti & Lazzati (2000), the cooling time (in the observer frame) can be written as:

\[
t_{\text{cool}} \sim 10^{-7} \frac{\epsilon_e^2 \Gamma_2}{\nu_{\text{MeV}}^2 (1 + U'_r/U'_B)(1 + z)} \text{ s},
\]

where \( U_r \) is the radiation energy density. Note that in Eq. (2) \( \epsilon_B \) does not appear (if not for the \( U_r/U_B \) term), and that \( \epsilon_e \) is bound to be less than unity.

2.3 Cooling must be fast

The smallest variability timescales observed in the prompt emission of GRBs are of the order of a few milliseconds. By themselves, these short timescales imply shorter still cooling timescales: how can the flux decrease if particles do not cool?

2.4 Predicted synchrotron spectrum

Since the shortest integration times are of the order of 1 s, the observed spectrum is always the time integrated spectrum produced by a rapidly cooling
particle distribution.

Since $t_{\text{cool}} \propto 1/\gamma$, in order to conserve the particle number, the instantaneous cooling distribution has to satisfy $N(\gamma,t) \propto 1/\gamma$. When integrated over time, the contribution from particles with different Lorentz factors is ‘weighted’ by their cooling timescale $\propto 1/\gamma$. Therefore the predicted (integrated) flux spectrum is

$$F_\nu \propto t_{\text{cool}} N(\gamma) \dot{\gamma}(d\gamma/d\nu) \propto \nu^{-1/2},$$

extending from $\sim 1$ keV to $h\nu_{\text{peak}} \sim \text{MeV}$ energies. We thus conclude that, within the assumptions of the internal shock synchrotron model, a major problem arises in interpreting the observed spectra as synchrotron radiation. We stress that the “line of death” of the synchrotron scenario does not correspond to spectra harder than $F_\nu \propto \nu^{1/3}$, as generally believed, but to spectra harder than $F_\nu \propto \nu^{-1/2}$, a much more severe condition: most of the burst spectra do not satisfy it (see e.g. Preece et al. 1998; Lloyd & Petrosian 1999).

Ghisellini, Celotti & Lazzati (2000) have discussed possible ‘escape routes’, such as deviations from equipartition, fastly changing magnetic fields, strong cooling by adiabatic expansion and re–acceleration of the emitting electrons. None of these possibilities help. The drawn conclusion is that the burst emission is probably produced by another radiation process.

### 3 Efficiency of internal shocks

Colliding shells with masses $m_1$, $m_2$, moving with bulk Lorentz factors $\Gamma_2 > \Gamma_1$ will dissipate part of their initial bulk kinetic energy with an efficiency $\eta$ given by

$$\eta = 1 - \Gamma_f \frac{m_1 + m_2}{\Gamma_1 m_1 + \Gamma_2 m_2}$$

where $\Gamma_f = (1 - \beta_f^2)^{-1/2}$ is the bulk Lorentz factor after the interaction and is given through (see e.g. Lazzati, Ghisellini & Celotti 1999)

$$\beta_f = \frac{\beta_1 \Gamma_1 m_1 + \beta_2 \Gamma_2 m_2}{\Gamma_1 m_1 + \Gamma_2 m_2}.$$

Note that the fraction $\eta$ is not entirely available to produce radiation, since part of it is in the form of hot protons and magnetic field. Therefore, as long as the ratio $\Gamma_2/\Gamma_1$ is smaller than a few, the corresponding efficiency is small. One could invoke much larger ratios, as in Beloborodov (2000), but in this case another process, yet to be discussed, becomes relevant, namely the Compton drag suffered by a fast shell in the radiation field already produced.
by the collisions of previous shells. The final outcome is difficult to compute, since it is very likely that in this situation copious pair production occurs, complicating any simple description of the process.

4 Alternatives

In the previous sections we have discussed two serious problems for the synchrotron interpretation of the prompt emission and a more general problem regarding the efficiency of the internal shock scenario. We are then motivated to search for alternatives for the main radiation mechanism of the bursts, and, more generally, to the internal shock scenario.

4.1 Comptonization

In the synchrotron shock scenario, one assumes that leptons are accelerated almost instantaneously to relativistic velocities, and then radiate. Typical energies are estimated assuming quasi–equipartition between the different forms of energy (in protons and in magnetic field). Ghisellini & Celotti (1999) have investigated instead the alternative case in which the leptons are accelerated slowly, in a time comparable to that needed for one shell to cross the other. The other assumptions of the internal shock scenario (i.e. intermittent fireball wind, shell mass, typical values of the magnetic field) where left unchanged with respect to the standard scenario. What we found is that the accelerated particles in this case do not attain very large relativistic energies, because the acceleration and the cooling rates balance at $\gamma < 2$. In these conditions the accelerated particles produce self–absorbed cyclo–synchrotron emission, and scatter these photons multiple times to form a quasi–saturated Comptonization spectrum (for other models using Comptonization as the main radiation process see Thompson 1994; Liang 1997, Stern 1999). Since the typical energy of the particles is small, the resulting spectrum is very similar to the one produced by a perfect Maxwellian distribution, even if the actual distribution is different. In other words, the predicted spectrum is $F_\nu \propto \nu^\delta$ ending in a Wien peak, whose importance with respect to the power law part of the spectrum is controlled by the Comptonization parameter $y$ and the particle optical depth $\tau_T$. Since the $\nu^\delta$ slope is a saturated value, it is appropriate in a large region of the optical depth -- temperature parameter space. Furthermore, the temperature $T$ is controlled by electron–positron pair processes: if $T$ is too large, the produced $\gamma$–rays interact to form pairs, which share the available energy and lower the temperature. This thermostat effect can fix the temperature (at least in a steady state plasma, so far the only studied
in detail) to less than 50 keV. The observed spectrum should then peak at 
\( h\nu \sim 3kT\Gamma \sim a \text{ few MeV} \). Since detailed time dependent studies are still 
lacking, it is difficult to predict exactly the Comptonized spectrum and its 
behavior. However, for this mechanism to work, it requires an optical depth 
of a few and a Comptonization parameter \( y \sim 10 \).

4.2 Compton drag

Excesses in the late afterglow optical light curves (Bloom et al. 1999; Galama 
et al. 2000; Björnsson et al. 2000); iron lines in emission in X–ray afterglows 
(Piro et al. 1999, 2000, Yoshida et al. 1999; Antonelli et al. 2000) and iron 
absorption edge (Amati et al. 2000) have revived the interest in the association 
between GRBs and Super/Supra/Hyper–Novae. If the burst explodes soon 
after or during a supernova explosion, then the fireball will expand in a dense 
photon environment, and it can be decelerated by the Compton drag effect 
(Lazzati et al., 2000). In this case there will be direct transformation of bulk 
energy into radiation, without the need to randomly accelerate the emitting 
particles. Furthermore, the fireball starts to produce radiation even when 
optically thick.

The required existing seed radiation field is indeed very large, such as the 
one produced by the walls of the funnel of an hypernova or by the just born 
remnant of a supernova exploded hours before the bursts. It is instead more 
problematic to decelerate the fireball if the seed photon field is produced by 
the remnant exploded a few months before the burst, because in this case the 
characteristic size of the remnant is already large, and the radiation is diluted.

The characteristic frequency of the scattered radiation is \( \nu \sim 2\Gamma^2\nu_0 \) where 
\( \nu_0 \) is the typical frequency of the incident seed photon. Most of the emission 
is produced when the fireball has an optical depth around unity, because 
this corresponds to the largest volume within which most of the ambient 
photons are scattered. If the process is efficient it can decelerate the fireball, 
which then scatter radiation with different \( \Gamma \) factors. Furthermore, in the 
case of a GRB born in a funnel of an hypernova, the walls of the funnel 
will be characterized by a distribution of temperatures (hotter in the inner 
parts). Therefore, even if the locally produced spectrum is blackbody–like, 
the time–integrated radiation is a superposition of blackbody spectra, each 
one characterized by a different effective observed temperature \( T_{\text{obs}} \sim 2TT^2 \).

Some examples of computed spectra in these conditions are plotted in Fig. 1, 
for a fireball of total energy \( 5 \times 10^{51} \text{ erg} \), expanding in a funnel of semiaperture 
angle \( \psi = 0.2 \), in a star of radius \( R_{\text{star}} = 10^{13} \text{ cm} \).

The initial bulk Lorentz factor is \( \Gamma = 30, 100, 300 \) in the three examples
shown. Since the fireball energy is kept fixed, a small $\Gamma$ correspond to a large fireball mass and viceversa. The efficiency of the process is then dependent of $\Gamma$ since the energy loss rate is $\propto \Gamma^2$.

For the adopted parameters, the spectrum peaks at 0.1–10 MeV, has a steep high energy tail, and a low energy $\nu^2$ slope. While this is in qualitative agreement with what observed, we point out that the low energy slope of this spectrum (the $\nu^2$ part) is a clear prediction of this model. It is in fact produced quite naturally, being the blackbody input spectrum boosted by the square of the Lorentz factor that the fireball has soon after it has become transparent. Instead, other models would have difficulties in explaining it, since synchrotron self-absorption occurs at much lower frequencies. In Fig.
we have indicated the energy range between 10 and 150 keV, appropriate for the high energy instrument onboard the SWIFT satellite, which can be particularly revealing in this respect.

4.3 Both?

Consider a fireball consisting of several shells (as an approximation of an inhomogeneous wind) crossing the dense photon environment of an hypernova funnel. If the process is efficient, the first shells will decelerate as a result of the intense Compton drag, but doing so, they will free the funnel cavity of photons. Therefore the later shells will suffer less Compton drag, especially along the axis of the funnel. This have important consequences:

- Internal shocks between first and later shells will develop even if the initial velocities are equal.
- Later shells will be faster along the axis than close to the funnel walls, where they can be dragged by the newly produced seed photons.
- Instabilities can occur in the funnel, more likely close to funnel walls, leading to strong shocks with dense material. This in turn favors inverse Compton as main radiation process.

All this is admittedly very qualitative, but worth to be investigated.

5 Conclusions

The synchrotron interpretation of the prompt emission of GRBs faces a severe problem: the synchrotron process is in fact very efficient, implying very short cooling timescales, shorter than the dynamical time (the light crossing time across the shell width). All the spectra obtained so far are time integrated over millions of cooling times, and are then produced by a cooling particle population, whose expected spectrum is much softer than observed. On the contrary the afterglow emission can well be due to the synchrotron process: in this case the much lower value of the typical magnetic field yields longer cooling timescales with incomplete cooling of the particle distribution.

We have explored alternatives such as Comptonization by a quasi–thermal particle distribution, whose temperature is kept small by electron–positron feedbacks, and the Compton drag process, requiring a very dense pre–existing photon field and the association of GRBs with just exploded (or about to explode) supernovae.
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References

1. Amati L. et al., 2000, Science, 290, 953
2. Beloborodov A.M., 2000, ApJ, 539, L25
3. Chiang J., 1999, ApJ, 514, 856
4. Cohen E., Katz J.I., Piran T., Sari R., Preece R.D. & Band D.L., 1997, ApJ, 488, 330
5. Ghisellini G. & Celotti A., 1999, ApJ, 511, L93
6. Ghisellini G., Celotti A. & Lazzati D., 2000, MNRAS, 313, L1
7. Ghisellini G., Lazzati D., Celotti A. & Rees M.J., 2000, MNRAS, 316, L45
8. Kumar P., 1999, ApJ, 523, L113
9. Lazzati D., Ghisellini G., Celotti A. & Rees M.J., 2000, ApJ, 529, L17
10. Lazzati D., Ghisellini G. & Celotti A., 1999, MNRAS, 309, L13
11. Liang E.P., 1997, ApJ, 491, L15
12. Lloyd N.M., Petrosian V., 1999, ApJ, 511, 550
13. Mészáros, P. & Rees, M.J., 1993, ApJ, 405, 278
14. Piro L. et al., 1999, ApJ, 514, L73
15. Piro L. et al., 2000, Science, 290, 955
16. Preece R.D., Briggs M.S., Mallozzi R.S., Pendleton G.N., Paciesas W.S. & Band D.L., 1998, ApJ, 506, L23
17. Sari R. & Piran T., 1997, MNRAS, 287, 110
18. Sari R., Piran T. & Narayan R., 1998, ApJ, 497, L17
19. Spada M., Panaitescu A., Mészáros, P., 2000, ApJ, 537, 824
20. Stern B., 1999, in High Energy Processes in Accreting Black Holes, ASP Conf. Series, Vol. 161, eds. J. Poutanen and R. Svensson, 277
21. Thompson C., 1994, MNRAS, 270, 480
22. Yoshida A. et al., 1999, Astr. Ap. Suppl, 138, 433