Hard GRB spectra: thermal vs non–thermal emission

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Abstract. We consider the evidence for very hard low energy spectra during the prompt phase of Gamma Ray Bursts (GRB). In particular we examine the spectral evolution of GRB 980306 together with the detailed analysis of some other bursts already presented in the literature (GRB 911118, GRB 910807, GRB 910927 and GRB 970111), and check for the significance of their hardness by applying different tests. The hard spectra of these bursts and their evolution constrain several non–thermal emission models, which appear inadequate to account for these cases. The extremely hard spectra at the beginning of their prompt emission are also compared with a black body spectral model: the resulting fits are remarkably good. These findings on the possible thermal character of the evolving spectrum and their implications on the GRB physical scenario can be considered in the frameworks of photospheric models for a fireball which is becoming optically thin, and of the Compton drag model. Both models appear to be qualitatively and quantitatively consistent with the found spectral characteristics.

1. Introduction

Since their discovery, the time resolved spectral analysis of GRBs has been a testing ground–floor for the models proposed for the γ–ray prompt emission (Ford et al. 1995; Preece et al. 2000). Nonetheless, the mechanism(s) responsible for their emission is still an open problem (Ghisellini 2003). Different authors (Crider et al. 1997, 1999; Preece et al. 1998, 2002; Ghirlanda et al. 2002) have shown that the low energy photon spectrum (typically represented by a powerlaw \( N(E) \propto E^\alpha \)) can be harder than the limit of the optically thin synchrotron model \( N(E) \propto E^{-2/3} \), Katz 1994; Tavani 1996) which is the most popular mechanism proposed for interpreting the burst emission. Modifications of the simplest optically thin synchrotron model (Lloyd & Petrosian 2000, 2002; Medvedev 2001) or variants based on Comptonization (Liang et al. 1997; Ghisellini & Celotti 1999; Lazzati et al. 2000) have been proposed to solve the inconsistency between theory and observations. All these models predict different limits for the low energy spectral hardness and can be directly tested by the comparison with the hardest bursts observed by BATSE.
We present the results of the time resolved spectral analysis of 5 bursts with a low energy spectral component harder than a flat photon spectrum, i.e. $\alpha \geq 0$, for most of their duration. These results are shown to constrain the above emission models (Ghirlanda, Celotti & Ghisellini 2003).

Another interesting aspect of GRB spectra which we consider is their possible thermal character, which is predicted by the fireball model (Goodman 1986; Paczynski 1986). We find that the spectrum in the initial phase of these extremely hard bursts is successfully fitted with a thermal black body emission. The interpretations and implications of these results are discussed (Ghirlanda et al 2003) in the framework of a photospheric (e.g. Mészáros & Rees 2000, Daigne & Mockovitch 2002) and of the Compton drag model (Lazzati et al. 2000; Ghisellini et al. 2000).

![Figure 1](image.png)

**Figure 1.** Light curve (top panels) and best fit parameters (photon spectral index and peak energy - mid and bottom panel, respectively) for GRB 980306 (left) and GRB 911118 (right). Horizontal lines mark the limits $\alpha = -2/3$ and $\alpha = 0$. The filled circles indicate the spectra which have been fitted also with a blackbody model.

2. Results

GRB 980306 represents a newly discovered case of hard burst. The spectral evolution of its first 6 s is reported in Fig.1 (left panel). The evolution of $\alpha$ (mid panel of Fig.1) indicates that, for most of the pulse, the low energy photon spectrum is harder than $E^0$. The maximum hardness ($\alpha = 1.1 \pm 0.2$) is reached at $t \sim 1.5$ s after the trigger.
In GRB 911118 (Fig. 1, right panel) the low energy spectral index is \( \alpha \geq 0 \) for the first \( \sim 6 \) s (32 spectra, phase A) The hardest photon spectrum (at \( t \sim 1.5 \) s after the trigger) has \( \alpha = 0.74 \pm 0.13 \).

In order to have homogeneous results we also reanalyzed three bursts (GRB 910807, GRB 910927, GRB 970111) already presented in the literature for their exceptional low energy spectral hardness (Crider et al. 1997, 2000; Frontera et al. 2000; Preece 2002).

Considering the relevance of these 5 GRBs for the comparison with the models, we also tested the independence of their low energy spectral hardness from possible sources of systematic error such as the detector response, the background calculation or the high energy spectral component. Moreover, we directly verified the low energy spectral hardness comparing the instrumental spectra with a simulated flat spectrum. These tests (Ghirlanda et al. 2003) indicate that most of the time resolved spectra of these bursts are harder than \( E^0 \) at more than \( 3\sigma \).

As anticipated, we performed fits on the hardest spectra also with a black body model. In most of these bursts the initial \( 1.5 \) s of their emission is consistent with a black body with a temperature that decreases with time as roughly \( T_{BB} \propto t^{-1/4} \) starting form \( kT \sim 100 \) keV (Ghirlanda et al. 2003).

3. Discussion

GRB 980306 and 911118, together with GRB 910807, 910927 and 970111 represent a challenge for the proposed emission processes. Their low energy photon spectrum is harder than \( N(E) \propto E^0 \) for a major part of the pulse/s reaching a maximum hardness of \( E^{1.5} \). These results are inconsistent with the optically thin synchrotron model which can not account for spectra harder than \( E^{-2/3} \) (Katz 1994). Also its variants like synchrotron self absorption (Papathanassiou 1999; Granot, Piran & Sari 2000), small pitch angles of the emitting particles (Lloyd & Petrosian 2000) or Jitter radiation (Medvedev 2001) can produce a spectrum at most as hard as \( N(E) \propto E^0 \), which is not compatible with the totality of these findings. Comptonization models (Liang et al. 1997; Ghisellini & Celotti 1999) also have difficulties, although they are consistent with very hard spectra in a limited range of energies.

The possible thermal character of the initial phase of all these 5 bursts can be interpreted as the emission of the fireball shells when they reach the transparency radius (Paczynski 1986; see also Daigne & Mockovetch 2002). For typical fireball parameters and using our observational findings this radius results \( R(\tau \sim 1) \sim 5 \times 10^{13} \) cm and the corresponding bulk Lorentz factor is \( \Gamma \sim 1000 \). An alternative scenario is the production of an observed thermal spectrum by the Compton drag of soft (seed) photons due to the fireball bulk motion (Lazzati et al. 2000). In this case the seed photons are required to have a temperature of \( \sim 5 \times 10^4 \) K in order to produce the observed thermal spectrum. These results are consistent with the typical values assumed in the theory of GRBs (e.g., Rees & Mészáros 1994).

At present, we are not able to discriminate between the photospheric and the Compton drag scenario. Consider also that emission at times greater than a few seconds can well be due to other processes, possibly linked to internal shocks.
starting to dominate at later phases. However, a key difference between the two scenarios is the fact that the seeds photons for the Compton drag process can be “used” only by the first shells, because the time needed to refill the scattering zone with new seeds exceeds the duration of the burst. Therefore observing black body emission for a long time, or during the rising phase of two time resolved peaks of the same GRB would be difficult to explain in terms of the Compton drag process.

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References

Crider A., Liang E.P., Smith I.A., 1997, ApJ, 479, L39
Crider A. et al., 1999, ApJ, 519, 206
Crider A. & Liang E.P., 2000, ApJ, 127, 283
Daigne F. & Mochkovitch R., 2002, MNRAS, 336, 1271
Ford L.A., Band D.L. & Matteson J.L., 1995, ApJ, 439, 307
Frontera F., Amati L., Costa E., et al., 2000, ApJS, 127, 59
Ghirlanda G., Celotti A. & Ghisellini G., 2002, A&A, 393, 409
Ghirlanda G., Celotti A. & Ghisellini G., 2003, subm. to A&A (astro-ph/0210693)
Ghisellini G. & Celotti A., 1999, ApJ, 511, L93
Ghisellini G., Lazzati D., Celotti A. & Rees M.J., 2000, MNRAS, 316, L45
Ghisellini G. 2003, astro-ph/0301256 see also these Proceedings
Goodman, 1986, ApJ, 308, L47
Granot J., Piran T. & Sari R., 2000, ApJ, 534, L163
Katz J.I., 1994, ApJ 432, L107
Lazzati D., Ghisellini G., Celotti A. & Rees M.J., 2000, ApJ, 529, L17
Lloyd N.M. & Petrosian V., 2000, ApJ, 543, 722
Lloyd N.M. & Petrosian V., 2002, ApJ, 565, 182
Liang E., Kusunose M., Smith I.A. & Crider A., 1997, ApJ, 479, L35
Medvedev M.V., 2001, astro-ph/0001314
Mészáros P. & Rees M.J., 2000, ApJ, 530, 292
Paczynski B., 1986, ApJ, 308, L43
Papathanassiou H., 1999, A&AS, 138, 525
Preece R.D. et al 1998, ApJ, 506, L23
Preece R.D. et al., 2000, ApJS, 126, 19
Preece R.D., Briggs M.S., Mallozzi R.S., Pendleton G.N., Paciesas W.S. & Band D.L., 2002, ApJ, 518, 1248
Rees M.J. & Mészáros P., 1994, ApJ, 430, L93
Tavani M., 1996, ApJ, 466, 768