Shape of the Decay Phase of Gamma-Ray Burst Pulses

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Abstract. We study the decay phase of GRB pulses belonging to the large subsample for which two important correlations between spectral hardness and intensity, and spectral hardness and photon fluence, respectively, are valid. These pulses exhibit a common temporal behavior, i.e., the spectral hardness and intensity of the decay phase of the pulses follow a reciprocal function in time.

INTRODUCTION

The spectral evolution for the decay phase of pulses in the light curve of gamma-ray bursts (GRBs) is described by two well-established empirical relations: i) the hardness-intensity correlation (HIC) [1], and ii) the hardness-photon fluence correlation (HFC) [2]. The HIC relates the instantaneous photon flux, $N(t)$ (in units of photons cm^{-2} s^{-1}), and a measure of the "hardness", e.g., the peak energy, $E_{\rm pk}(t)$, of the instantaneous $E^2 N_{\rm E}(E,t)$ spectrum,

$$E_{\rm pk}(t) = E_{\rm pk,0} \left[\frac{N(t)}{N_0}\right]^{\delta}, \tag{1}$$

where δ is the correlation index. The HFC relates the spectral hardness and the time-integrated photon flux,

$$E_{\rm pk}(t) = E_{\rm pk,0} e^{-\Phi(t)/\Phi_0}, \tag{2}$$

where $\Phi(t)$ is the photon fluence $\equiv \int_0^t N(t')\,dt'$ (in units of cm^{-2}) integrated from the time of $E_{\rm pk,0}$, and Φ_0 is the exponential decay constant.

In Ryde & Svensson [3] the combination of these two correlations was studied. Neither the HIC nor the HFC includes any explicit time dependence of the spectral evolution. However, combined they do, as the fluence is the time integral of the flux. This was used to find a compact and quantitative description of the time evolution of the decay phase of a GRB pulse. This gives constraints on the pulse profiles, which should reflect the underlying physical mechanisms.

DESCRIPTION OF THE DECAY PHASE

The combination of the two empirical relations, given by equations (1) and (2), makes the description of the temporal behavior complete. This can be expressed as differential equations either for $E_{\rm pk}(t)$ as

$$-\frac{dE_{\rm pk}(t)}{dt} = \frac{N_0}{\Phi_0 (E_{\rm pk,0})^{1/\delta}} E_{\rm pk}^{1+1/\delta}, \tag{3}$$

or for $\Phi(t)$ as

$$\frac{d\Phi(t)}{dt} = N_0 e^{-\Phi(t)/\delta\Phi_0}, \tag{4}$$

or for $N(t)$ as

$$-\frac{dN(t)}{dt} = \frac{1}{\delta\Phi_0} N^2(t). \tag{5}$$

Integrating these results, the time evolution of the peak energy will be given by

$$E_{\rm pk}(t) = \frac{E_{\rm pk,0}}{\left[1 + \frac{N_0}{\delta\Phi_0} t\right]^{\delta}}, \tag{6}$$

the time evolution of the fluence by

$$\Phi(t) = \delta\Phi_0 \ln\left[1 + \frac{N_0}{\delta\Phi_0} t\right], \tag{7}$$

and, finally, the time-evolution of the intensity will be given by

$$N(t) = \frac{N_0}{1 + \frac{N_0}{\delta\Phi_0} t}, \tag{8}$$

or equivalently by

$$\frac{1}{N(t)} = \frac{1}{N_0} + \frac{t}{\delta\Phi_0}. \tag{9}$$

Equation (8) is an important result, as it describes how the intensity declines with time in the decay phase of a GRB pulse belonging to the subgroup of pulses for which both the two empirical relations, equations (1) and (2), are valid. The reciprocal, instantaneous intensity is a linear function in time, Equation (9). This should be compared to the generally discussed exponential decay, e.g., in the terms of a FRED (fast rise, *exponential* or *stretched exponential* decay) often used to characterize single pulses within GRBs (e.g., Norris et al. [4]). Our result, on the other hand, is an analytical result following directly from the two empirical relations (1) and (2).

As shown by equation (7), the fluence increases logarithmically with time. This divergent behavior must eventually change, when the emission of radiation changes behavior, terminates, or shifts out of the observed spectral range.

The hardness, represented by the peak energy, $E_{\rm pk}$, also declines reciprocally with time, but it is stretched by the δ-power. A comparison between the intensity decline and the $E_{\rm pk}$ decline is shown, for instance, in Ford et al. [6].

The time evolution is fully defined through four parameters describing the empirical relations, for instance, by N_0, $E_{\rm pk,0}$, Φ_0, and δ.

BATSE SAMPLE

We have studied a large, complete sample of 83 GRB pulses observed by the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma-Ray*

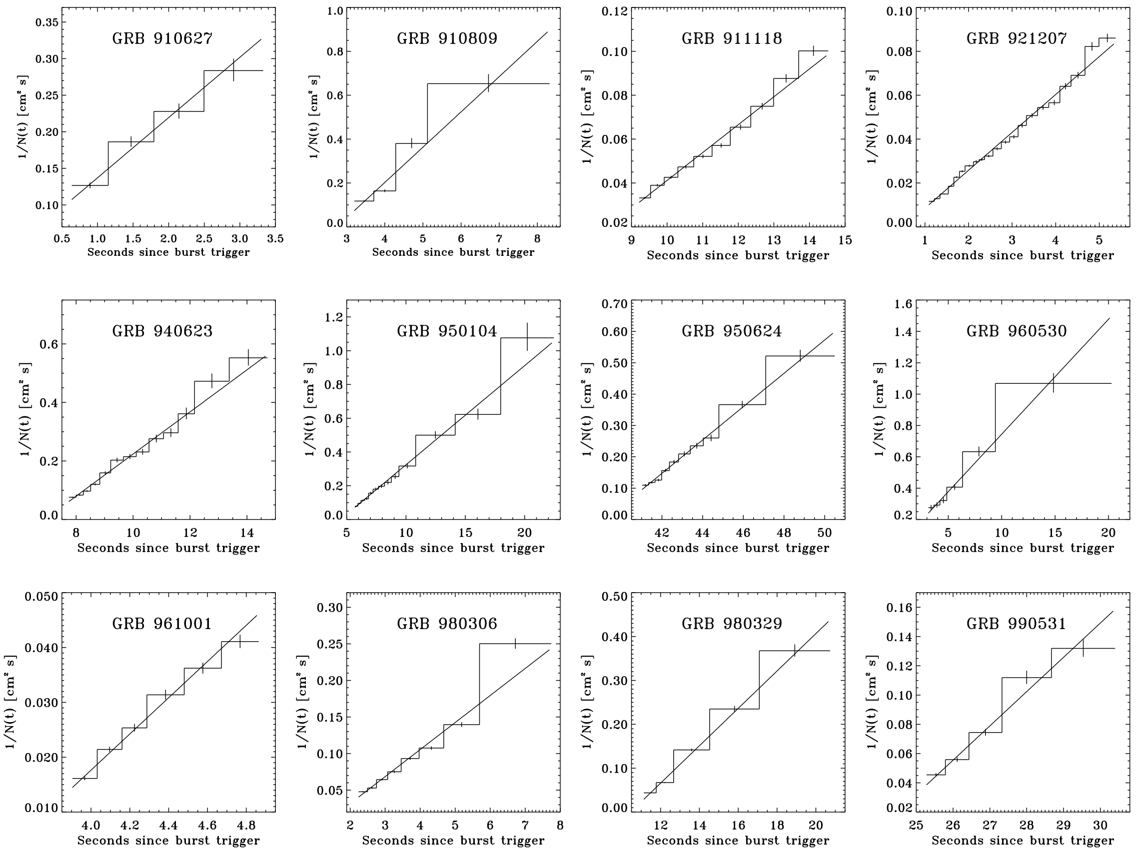

FIGURE 1. Observed background-subtracted photon flux light curves of the decay phases of a few cases in the studied sample. The linear behavior of $1/N(t)$ is shown. See the text for details.

TABLE 1. The decay parameters for a sample of bright BATSE burst pulses. The most prominent pulse in the light curves is studied.

Burst Name	N_0 [cm^{-2} s^{-1}]	$E_{\mathrm{pk},0}$ [keV]	τ [s]	δ	Φ_0[a] [cm^{-2}]	Time[b] [s]
GRB 910627 (#451)	9.3 ± 0.5	440 ± 250	1.3 ± 0.2	1.8 ± 1.2	6.7 ± 3.2	2.69
GRB 910809 (#660)	13.7 ± 0.8	1060 ± 360	0.46 ± 0.05	1.09 ± 0.25	5.6 ± 1.0	5.12
GRB 911118 (#1085)	32.1 ± 0.4	123.2 ± 2.4	2.46 ± 0.07	0.63 ± 0.03	128 ± 7	5.31
GRB 921207 (#2083)	99.5 ± 1.3	474 ± 9	0.58 ± 0.01	0.90 ± 0.02	64.1 ± 1.5	4.29
GRB 940623 (#3042)	16.3 ± 0.4	523 ± 68	0.85 ± 0.04	0.78 ± 0.09	18.4 ± 2.6	6.98
GRB 950104 (#3345)	14.0 ± 0.4	140 ± 18	1.22 ± 0.07	0.41 ± 0.10	36 ± 9	16.77
GRB 950624 (#3648)	10.5 ± 0.2	300 ± 15	1.80 ± 0.08	1.07 ± 0.05	16.9 ± 0.9	9.47
GRB 960530 (#5478)	4.1 ± 0.2	187 ± 14	3.3 ± 0.4	0.86 ± 0.11	15.2 ± 2.3	17.15
GRB 961001 (#5621)	69.1 ± 1.8	440 ± 60	0.44 ± 0.03	1.1 ± 0.2	26 ± 5	0.96
GRB 980306 (#6630)	24.7 ± 0.6	253 ± 8	1.10 ± 0.04	1.01 ± 0.04	27.9 ± 1.2	5.50
GRB 980329 (#6665)	34.3 ± 1.0	240 ± 24	0.68 ± 0.03	0.21 ± 0.09	103 ± 36	9.60
GRB 990531 (#7592)	25.9 ± 0.8	138 ± 7	1.65 ± 0.13	0.69 ± 0.09	62 ± 8	5.12

[a] As fitted from Eq. (2).
[b] Length of the time interval during which the decay was studied.

Observatory (CGRO), see [3]. We find that the behavior described above is common ($\sim 45\%$). There are also several examples of varying behavior of the HIC within single pulse structures. In Ryde & Svensson [5], other behaviors that do not follow the common description (Eqs. 1, 2) are studied. According to the prescription, a pulse profile that does not show this time behavior will, of necessity, have a different HIC or HFC. The light curve is much better suited for statistical analysis as the noise (counting statistics) is relatively small (compared to the HIC or the HFC).

Figure 1 shows several cases which follow the description. They are presented as $1/N(t)$ to clearly emphasize the reciprocal linear behavior arrived at in Equation (9). The data are rebinned to a signal-to-noise-ratio of at least 30. These fits to the data give the parameters N_0 and the time constant $\tau \equiv \delta\Phi_0/N_0$. Corresponding fits to the time evolution of $E_{\mathrm{pk}}(t)$ (eq. [6]) give $E_{\mathrm{pk},0}$ and δ. The results of the fits are given in Table 1. Over a time τ, the light curve decreases by a half. For most of the cases, the decay phase persists over more than 5τ with the pulse in GRB 980329 (#6665) covering 14 τ. Note that the time variable in Figure 1 is counted from the trigger time of the burst, while the time variable, t, in the text is counted from the peak of the pulse.

DISCUSSION

We have studied a subgroup of GRB pulses, for which the two empirical relations are valid and show that for these the decay phase of the pulse should be (with the characteristic time scale of the decay, the time constant, $\tau \equiv \delta\Phi_0/N_0$)

$$N(t) = \frac{N_0}{(1 + t/\tau)}; \tag{10}$$

$$E_{\mathrm{pk}}(t) = \frac{E_{\mathrm{pk},0}}{(1+t/\tau)^{\delta}}, \tag{11}$$

where the initial values are $(N_0, E_{\mathrm{pk},0})$ and the number of additional parameters is limited to two, the time constant τ $[N(t=\tau)=N_0/2]$ and the HIC index δ. The peak energy has a similar time dependence as the intensity, differing only by the power law index δ. The exponential decay constant of the HFC is given by $\Phi_0 \equiv N_0\tau/\delta$. The formulation, given above is a condensate of the HIC and the HFC, each of which has been proven to be valid in most sufficiently bright GRB-pulses.

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