Track Jumps in Hardness-Intensity Correlations of GRB Pulse Decays

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Abstract. The hardness-intensity correlation (HIC), during the decay phase of gamma-ray burst pulses, can often be described by a simple power law. The pulse decays in multi-pulse bursts present power-law indices that are equal to within the errors. We find that in some pulses the HIC changes to a parallel power law, a feature that we graphically call a *track jump*. The use of the index constancy is proposed as an auxiliary tool for pulse identification and examples of its application are given.

INTRODUCTION

The understanding of the spectral and temporal evolution of gamma-ray bursts (GRBs) renders us important clues to the underlying processes giving rise to the phenomenon. The evolution has been studied both over the entire burst, giving the overall behavior, and over individual pulse structures (see, e.g., [1]). One important relation that characterizes the spectral evolution is that between some measure of the "hardness" of the spectrum and the instantaneous flux (or intensity), usually referred to as the Hardness-Intensity Correlation (HIC). It was first studied in GRBs by Golenetskii et al. [2], and later by others like Kargatis et al. [3,4]. They found that in many cases, during the decay phase of strong individual pulses, the HIC could be described by a simple power law relation $F \propto E_{\rm pk}^{\gamma}$, evolving from hard to soft. F represents the energy flux and $E_{\rm pk}$ is the energy at which the power is at its maximum, i.e., the peak in the $EF_{\rm E}$-spectrum, that is used as a measure of the spectral hardness. In this work we will discuss cases where the HIC can be divided into two power laws of identical indices. These cases show what we will refer to graphically as a *track jump*.

We conducted a study [5] on multi-pulse bursts over a complete sample. We showed that, although the HIC indices present a broad distribution among different bursts, their values are equal to within the errors when comparing pulses within a burst. The probability of a random coincidence was negligible ($p < 10^{-5}$).

The measure of the flux $F \equiv \int F_{\rm E} dE$ can be affected by the finite energy band of the detector, especially when the spectrum is broad or peaks close to the boundaries of the energy range. The existence of a separate soft component and/or additional weak pulses could also affect the analysis, changing the shape of the spectrum. This motivated us to introduce an alternative representation of the flux, given by the value of EF_E at $E{=}E_\mathrm{pk}$, which we will denote by ϕ. A more detailed discussion can be found in these proceedings [6]. Since ϕ is roughly proportional to the total flux, the HIC can again be described by a power law as $\phi \propto E_\mathrm{pk}^{\eta}$. In general, better correlation coefficients are found with this method. In addition, we observed a better constancy of the η power law indices, among pulses of the same burst, than when we compared the corresponding γ indices.

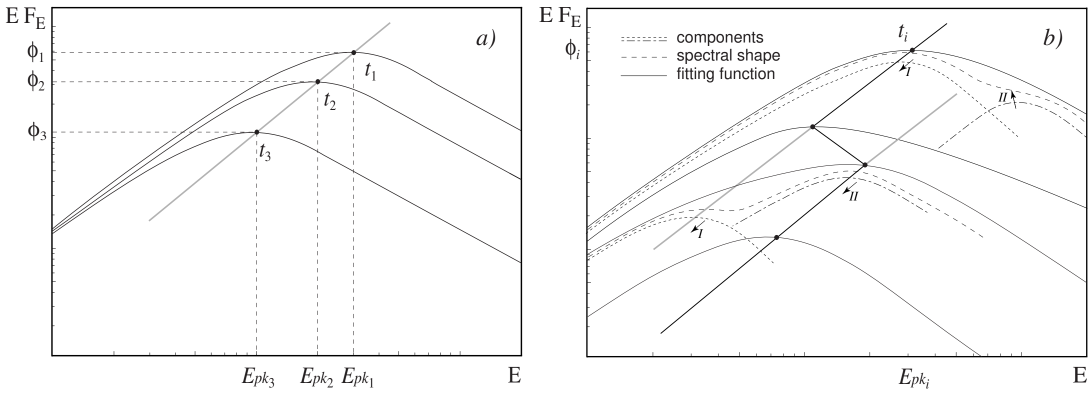

FIGURE 1. *a*) During pulse decays, in the EF_E representation, the spectral peaks evolve in time following a power law. *b*) The *track jumps* found in some cases can be explained with a two-component model. The figure shows a qualitative sketch. Each component evolves in a similar way, following approximately parallel tracks when decaying. However, the second is delayed in time and the "jump" occurs when it overcomes the first component. See the text for further details.

Figure 1a illustrates the observed evolution of $\phi(E_\mathrm{pk})$ along a *track* during the decay phase of a single pulse. When many pulses are present in the light curve of a burst, although there is no apparent general trend during the rising phases, they will follow almost parallel tracks during the decay phases. To actually observe this behavior, it is necessary that the pulses do not overlap significantly. Also, they need to be bright and long enough to establish the direction of the *track*. As an example, the overall evolution of GRB 970420 (trigger #6198) is shown in Figure 2.

TRACK JUMPS

Our work was conducted on data taken by the Burst and Transient Source Experiment (BATSE) on board the *Compton Gamma-Ray Observatory*. We used the high-energy resolution burst data (HERB) which were reduced using standard procedures. The spectra were modeled using the empirical Band et al. [7] function.

Pulses are a common feature in the light curves of GRBs and appear to be their fundamental constituent [8,9]. An approach frequently employed is to identify each pulse as a single physical event. Depending on the model chosen, this event could

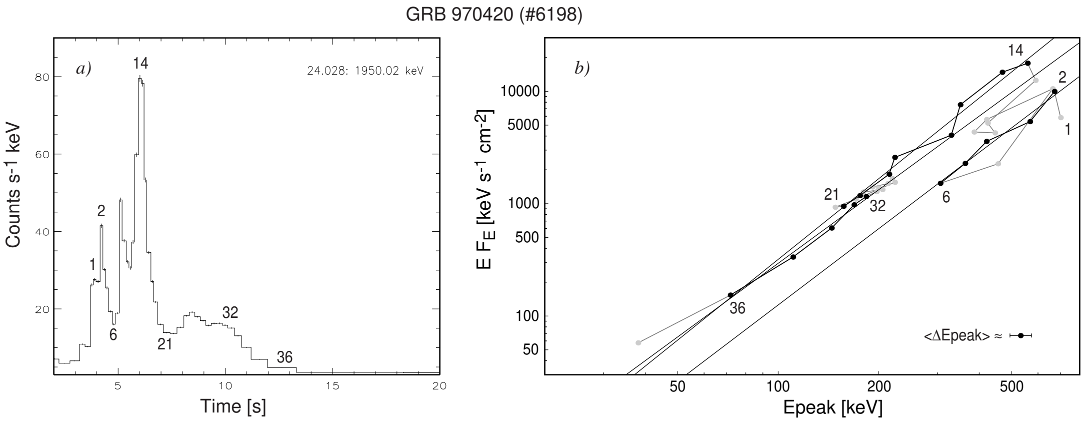

FIGURE 2. *a*) Count time history of GRB 970420 (#6198) showing the binning used to study the spectral evolution. The second pulse (at bin #8) actually consists of two close-lying pulses, which are seen in the 64-ms data. *b*) The peaks of the instantaneous spectra at successive times are represented by dots. Error bars are excluded for better visibility, and only a typical average value is shown separately. The numbers refer to the time-bins in (*a*). The decaying phases (dark dots) follow very good power laws with indices $\eta_1 = 2.25 \pm 0.20$, $\eta_2 = 2.40 \pm 0.15$, and $\eta_3 = 2.20 \pm 0.15$, equal to within the estimated errors.

be the collision between two expanding *internal* shells or the "activation" of a region on a single *external* shell. To validate this reductionistic method, it is essential to find common trends between pulses, such as the HIC that we describe here. But GRB light curves very often show a complex overlap of pulses and to attemp to separate them requires additional assumptions.

We show in Figure 3 the spectral evolution of GRB 950104 (#3345). Initially, the second decay has approximately the same HIC power law index as the first one. It then makes a change into a parallel track. Checking the 64-ms count time history, one can see that this *track jump* coincides with the presence of a small secondary peak which is hidden by the low resolution binning. The significance of this peak is somewhat marginal (3.2 σ), but the agreement with the direction of the first pulse track makes it a more compelling case. The power law indices obtained for the tracks are $\eta_1 = 0.77 \pm 0.05$, $\eta_2 = 0.79 \pm 0.03$, and $\eta_3 = 0.76 \pm 0.05$, equal to within the estimated errors. We show in the same way the case of GRB 970925 (#6397). Again, we have modeled the decay evolution with two power laws. There is now no clear indication of a secondary peak, although a small "bump" coincides with the *track jump*. The measured indices, $\eta_1 = 0.77 \pm 0.15$ and $\eta_2 = 0.86 \pm 0.05$, are again equal to within the errors.

As a likely explanation of the *track jumps*, we illustrate a two spectral component model in Figure 1*b*. The components follow identical directions during their decay phases. At some point the second component overcomes the first, the fitting routine finds a better χ^2 value shifting the Band function parameters to peak at a higher $E_{\rm pk}$, and the jump occurs. Note that due to the rather broad spectral shape, the change in the values of the asymptotic slopes of the Band function is an artifact of the fitting. The fitting routine finds the peaks by minimizing the χ^2 merit function. The errors are estimated evaluating the confidence region around the χ^2 minima. Since the spectral shape has a local maximum close to the absolute one, this produces an overestimation of $E_{\rm pk}$ errors. The alignment of the data points along the tracks proves that the shape features are real and not a random occurrence (see Figure 3).

Other workers [4,10] have fixed the parameters that control the asymptotic behavior of the Band function, to reduce the estimated errors of $E_{\rm pk}$. Such a solution provides more "stable" $E_{\rm pk}$ values, but a case like GRB 950104 (#3345) would be missed. It smoothes out the *track jump* in such a way that a single, steeper track is obtained for the whole decay.

The simplest interpretation of the *track jump* is to assume that it is produced by an overlapping secondary pulse. From this point of view, this feature is present also in cases like the one shown in Figure 2. The only difference is that there we can resolve the individual pulses in the light curve. We, therefore, propose to use the constancy of the HIC power law index, among pulses of the same burst, as an auxiliary method for pulse identification in overlapped pulses [5]. To identify *track jumps* with some confidence, the distance between tracks should be larger than the observed dispersion along individual tracks. Also a minimum number of points on each track is required to produce a resonable fit. We found few cases in our BATSE sample that meet these requirements. However, future instrumentation will allow higher time-spectral resolution and these criteria will then have a wider application.

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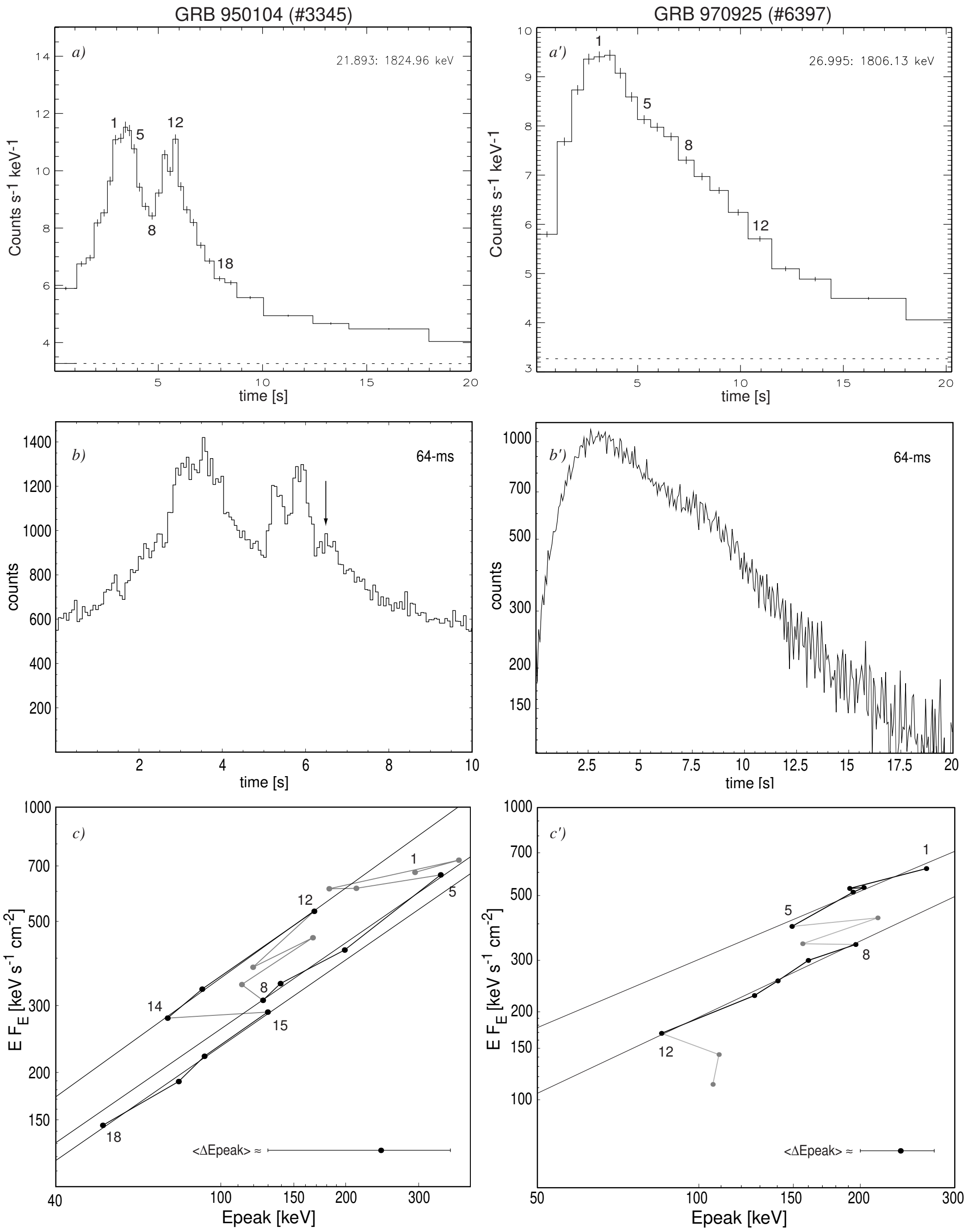

FIGURE 3. Spectral evolution of GRB 950104 (#3345) and GRB 970925 (#6397). *a*) Count time histories showing the binning used to study the spectral evolution ($S/N = 30$) and the background level (dashed line). *b*) The same using 64-ms time resolution data. *c*) The peaks of the instantaneous spectra at successive times are represented by dots. The numbers refer to the time-bins in (*a*). Error bars are excluded for better visibility, and only a typical average value is shown separately. The fitting procedure largely overestimates the errors in these cases. See discussion in the text.