SPECTRAL HARDNESS DECAY WITH RESPECT TO FLUENCE IN BATSE GAMMA-RAY BURSTS

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ABSTRACT

We have analyzed the evolution of the spectral hardness parameter $E_{pk}$ (the maximum of the $\nu F_\nu$ spectrum) as a function of fluence in gamma-ray bursts. We fit 41 pulses within 26 bursts with the trend reported by Liang & Kargatis, which found that $E_{pk}$ decays exponentially with respect to photon fluence $\Phi(t)$. We also fit these pulses with a slight modification of this trend, where $E_{pk}$ decays linearly with energy fluence. In both cases, we found the set of 41 pulses to be consistent with the trend. For the latter trend, which we believe to be more physical, the distribution of the decay constant $\Phi_0$ is roughly lognormal, where the mean of $\log_{10} \Phi_0$ is 1.75 ± 0.07 and the FWHM of $\log_{10} \Phi_0$ is 1.0 ± 0.1. Regarding an earlier reported invariance in $\Phi_0$ among different pulses in a single burst, we found probabilities of 0.49–0.84 (depending on the test used) that such invariance would occur by coincidence, most likely because of the narrow distribution of $\Phi_0$ values among pulses.

Subject headings: gamma rays: bursts — gamma rays: observations

1. INTRODUCTION

The discovery of a gamma-ray burst (GRB) optical counterpart with a measurable redshift seems to have shown that the sources are cosmological in origin (Djorgovski et al. 1997; Metzger et al. 1997). The observed fading multiwavelength afterglows are so far consistent with the simple relativistic blast-wave model (Mészáros & Rees 1997), which radiates via a synchrotron shock. However, the emission mechanism resulting in the prompt gamma rays remains a mystery. Studies of GRB spectral evolution have uncovered many trends that may be used to test possible emission mechanisms. In general, studies of GRB spectral evolution have focused on the “hardness” of bursts, measured either by the ratio between two detector channels or with more physical variables such as the spectral break or peak power energy $E_{pk}$ (Ford et al. 1995), which is the maximum of $\nu F_\nu$, where $\nu$ is photon energy and $F_\nu$ is the specific energy flux. Such hardness parameters were found to either follow a “hard-to-soft” trend (Norris et al. 1986), decreasing monotonically while the flux rises and falls, or to “track” the flux during GRB pulses (Golenetskii et al. 1983; Kargatis et al. 1994).

The discovery that $E_{pk}$ often decays exponentially in bright, long, smooth BATSE GRB pulses as a function of photon fluence $\Phi$ (equal to $\int_{\nu=\nu_0}^{\nu=\nu_f} F_\nu(t')dt'$; Liang & Kargatis 1996, hereafter LK96) provided a new constraint for emission models (Liang et al. 1997; Liang 1997; Daigne & Mochkovitch 1998). In their analysis, LK96 fitted the function

$$E_{pk}(t) = E_{pk(0)} \exp \left[ -\Phi(t)/\Phi_0^{LK} \right]$$

(1)

to 37 GRB pulses in 34 bursts. To interpret this empirical trend, they differentiated equation (1) to find

$$-dE_{pk}/dt = E_{pk} F_N/\Phi_0^{LK} \approx F_E/\Phi_0^{LK}$$

(2)

where $F_E = \int_{E=2000\text{keV}}^{E=30\text{keV}} E N(E)dE$ is the BATSE energy flux (see eq. [1] of LK96). In this paper, we wished to avoid the assumption that $E_{pk} F_N \approx F_E$. To do this, we directly tested the trend $-d(E_{pk})/dt = F_E/\Phi_0$ by integrating it to give us the function

$$E_{pk}(t) = E_{pk(0)} - \delta(t)\Phi_0$$

(3)

where $\delta(t)$ (equal to $\int_{t=0}^{t=t'} F_E(t')dt'$) is the BATSE energy fluence. We emphasize that this is not a fundamentally different trend from the form used in LK96.

The decay constant $\Phi_0^{LK}$ appeared to be invariant among pulses during some bursts analyzed in LK96, suggesting that individual pulses in a burst may originate in the same plasma. These discoveries coupled with the observed evolution of the spectral shape (Crider, Liang, & Preece 1998a) suggested that saturated inverse Comptonization may be a viable mechanism during the gamma-ray active phase of bursts (Liang et al. 1997), regardless of the distance scale (Liang 1997).

2. PROCEDURES

To determine the evolution of GRB spectral shapes, we examined high energy resolution data collected from the BATSE Large Area Detector (LAD) and Spectroscopy Detector (SD) on board the Compton Gamma Ray Observatory (CGRO; Fishman et al. 1989). We began with the 126 bursts that appear in Preece et al. (1998). These bursts were chosen for having a BATSE fluence (28–1800 keV) $> 4 \times 10^{-5}$ ergs cm$^{-2}$ or a peak flux (50–300 keV on a 256 ms timescale) $> 10$ photons cm$^{-2}$ s$^{-1}$. The counts from the detector most nearly normal to the line of sight of each burst (burst angle closest to 0) were background-subtracted and binned into time intervals each with a signal-to-noise ratio (S/N) of ~45 within the 28–1800 keV range. Such an S/N has been found to be necessary in time-resolved spectroscopy of BATSE GRBs (Preece et al. 1998).

We deconvolved the gamma-ray spectra of each time
interval using the Band et al. (1993) GRB function

\[
N_d(E) = \begin{cases} 
A \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left( - \frac{E}{E_0} \right), & (\alpha - \beta)E_0 \geq E, \\
\left[ \frac{(\alpha - \beta)E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \exp \left( \frac{E - E_0}{(100 \text{ keV})^{\alpha}} \right), & (\alpha - \beta)E_0 \leq E,
\end{cases}
\]

where \( A \) is the amplitude (in photons \(^{-1} \text{ cm}^{-2} \text{ keV}^{-1} \)) and \( E_0 = E_{pk}/(2 + \alpha) \). While LK96 assumed that \( \alpha \) and \( \beta \) were constant during the course of each burst, this has since been shown to be untrue with a larger data set (Crider et al. 1997). We thus left \( \alpha \) and \( \beta \) as free parameters in our fits.

At this point, we needed to select pulses within our bursts that we could use to test equations (1) and (3). Ideally, our pulses would not overlap other pulses and our method for choosing the time bins associated with a pulse would not be biased. Unfortunately, by forcing our time bins to have an equal separation, choosing the time bins associated with a pulse would not be possible without overlap, and our method for selecting these time bins would have to be abandoned. Nevertheless, we also fitted equation (1) to our pulses in this paper as a test of our interpretation of the energy fluence relation (eq. [3]) as opposed to the photon fluence relation (eq. [1]) is that the observed BATSE photon fluence is a poor representation of the bolometric photon fluence. The BATSE LAD energy window was designed to contain the peak of GRB energy spectra, not the peak of the photon spectra. By using energy fluence in place of photon fluence, we can avoid the shakier assumption that the BATSE LAD photon flux is proportional to the bolometric photon flux. LK96 had attempted this but found that statistical errors in \( \delta \) were too large to be useful. This was a result of their fixing \( \alpha \) and \( \beta \) in the spectral fitting. When we fitted the time-resolved spectra with variable \( \alpha \) and \( \beta \), we obtained much smaller errors for \( \delta \), which made testing the \( E_{pk}^{-\delta} \) relation possible. Nevertheless, we also fitted equation (1) to our pulses in this paper both for historical reasons and as a test of our interpretation.

Our next step was to test the \( E_{pk} \) fluence relations (eqs. [1] and [3]) with each of the selected pulses. Our motivation for emphasizing the \( E_{pk} \) energy fluence relation (eq. [3]) as opposed to the \( E_{pk} \) photon fluence relation (eq. [1]) is that we believe that the former represents a more physical quantity. It is possible (perhaps even likely) that the observed BATSE photon fluence is a poor representation of the bolometric photon fluence. The BATSE LAD energy window was designed to contain the peak of GRB energy spectra, not the peak of the photon spectra. By using energy fluence in place of photon fluence, we can avoid the shakier assumption that the BATSE LAD photon flux is proportional to the bolometric photon flux. LK96 had attempted this but found that statistical errors in \( \delta \) were too large to be useful. This was a result of their fixing \( \alpha \) and \( \beta \) in the spectral fitting. When we fitted the time-resolved spectra with variable \( \alpha \) and \( \beta \), we obtained much smaller errors for \( \delta \), which made testing the \( E_{pk}^{-\delta} \) relation possible. Nevertheless, we also fitted equation (1) to our pulses in this paper both for historical reasons and as a test of our interpretation.
3. RESULTS

We fitted both the $E_{pk}\Phi$ and the $E_{pk}\Phi^{\delta}$ relations to our 41 clean pulses using FTFEXY (Press et al. 1992). Table 1 summarizes the results for each of the pulses in our sample. Of course, $\Phi_0$ will only equal $\Phi_{pK}^0$ if $E_{pk}\Phi = E_{pk}\Phi^{\delta}$. Since the latter is not strictly true, we find that $\Phi_0 \approx \Phi_{pK}^0$. For completeness, we also show the plots of $E_{pk}$ versus $\delta$ and their fits in Figure 2.

From the $\chi^2$ and the number of fluence bins for each decay fit, we calculated the probability $Q$ of randomly getting a higher $\chi^2$ by chance. Thus, $Q \gtrsim 0.5$ represents very good fits, while $Q \sim 0$ represents poor fits. The $Q$ values from fits of equation (3) to our pulses appear in column (10) of Table 1. If $E_{pk}$ does indeed cool linearly with $\delta$ in all pulses selected for fitting, then when plotting the cumulative distribution of $Q$ values we would expect 10% of the pulses to have a $Q$ less that 0.1, 20% of the pulses to have a $Q$ less than 0.2, and so on. Figure 3 shows the cumulative distribution of $Q$ values for our pulses with acceptable fits. An excess of pulses with very high $Q$ values would suggest a biased pulse selection process. A Kolmogorov-Smirnov test ($P = 0.18$) applied to our distribution of $Q$ values suggests that the set of 41 pulses is not too biased and roughly follows the distribution we would expect if all of them are consistent with a linear decay of $E_{pk}$ with respect to energy fluence.

By fitting the $E_{pk}$ fluence law to the full observable duration of each pulse and not just the flux decay phase, we could characterize our pulses as “hard-to-soft.” None of our pulses required a “tracking” classification, although many of the ambiguous pulses excluded from this study

### TABLE 1

| BATSE Trigger (1) | Burst Name (2) | LAD (3) | $t_{max}$ (s) (4) | $\Delta \phi$ (MeV cm$^{-2}$) (5) | Bins (6) | $\Phi_{pK}^0$ (cm$^{-2}$) (7) | $\Phi_0$ (cm$^{-2}$) (8) | $E_{pk(0)}$ (keV) (9) | $Q$ (10) |
|-------------------|----------------|--------|-------------------|-------------------------------|--------|-----------------------------|---------------------------|-------------------------|--------|
| 4511.... | 910627 | 4 | 5.0 | 4.9 | 10 | 37 $\pm$ 5 | 51 $\pm$ 6 | 125 $\pm$ 7 | 0.206 |
| 5431.... | 910717 | 4 | 1.1 | 1.5 | 4 | 17 $\pm$ 3 | 12 $\pm$ 2 | 255 $\pm$ 14 | 0.251 |
| 6471.... | 910807 | 0 | 14.0 | 4.1 | 7 | 79 $\pm$ 17 | 59 $\pm$ 15 | 249 $\pm$ 11 | 0.664 |
| 6471.... | 910807 | 0 | 3.5 | 3.2 | 7 | 42 $\pm$ 5 | 35 $\pm$ 5 | 212 $\pm$ 8 | 0.299 |
| 9731.... | 911031 | 3 | 1.8 | 10.8 | 22 | 70 $\pm$ 9 | 62 $\pm$ 8 | 295 $\pm$ 18 | 0.965 |
| 9731.... | 911031 | 3 | 23.7 | 3.6 | 9 | 29 $\pm$ 10 | 24 $\pm$ 11 | 285 $\pm$ 49 | 0.991 |
| 1098.... | 911118 | 4 | 2.1 | 10.3 | 16 | 75 $\pm$ 5 | 61 $\pm$ 5 | 354 $\pm$ 10 | 0.016 |
| 1098.... | 911118 | 4 | 6.3 | 2.3 | 4 | 564 $\pm$ 569 | 446 $\pm$ 462 | 139 $\pm$ 3 | 0.714 |

### Notes
- Col. (1) is the BATSE trigger number.
- Col. (2) is the burst name, which is also the date the burst triggered in the format YYMMDD.
- Col. (3) is the number of the LAD that was used for processing.
- Col. (4) lists the $t_{max}$ from the Norris function fitted to the pulse.
- Col. (5) is the energy fluence within the bins selected for fitting in units of MeV cm$^{-2}$.
- Col. (6) gives the number of bins selected for fitting.
- Col. (7) is the fitted value $\Phi_{pK}^0$ for each pulse defined in eq. (1).
- Col. (8) and (9) are the fitted values of $\Phi_0$ and $E_{pk(0)}$ for each pulse as defined in eq. (3).
could be "hard-to-soft" or "tracking." Three of the pulses in our sample (BATSE triggers 2316, 3491, and 3870) contain pulses with negative values of $\Phi_0$. However, all three of these pulses are still consistent with a positive value of $\Phi_0$. We remind the reader here that large absolute values of $\Phi_0$ (like those in these three pulses) correspond to pulses with very little change in $E_{pk}$, where $1/\Phi_0 \equiv dE_{pk}/d\epsilon \approx 0$. In such cases, small statistical errors in $dE_{pk}/d\epsilon$ translate to very large statistical errors in $\Phi_0$. Even if all pulses decay monotonically from hard-to-soft, we should expect to see a few pulses to have negative values of $\Phi_0$. Since all of our pulses are consistent with a monotonic decay in $E_{pk}$, we adopt the hypothesis that all pulses behave this way for the remainder of this paper and drop these three pulses from our sample to simplify our calculations.

3.1. Distribution of $\Phi_0$

The distribution of fitted $\Phi_0$ values appears in Figure 4. It is roughly lognormal, where the mean of $\log_{10} \Phi_0$ is $1.75 \pm 0.07$ and the FWHM of $\log_{10} \Phi$ is $1.0 \pm 0.1$. This distribution likely suffers some selection effects. This
becomes obvious when one realizes that \( \Phi_0 \approx -\Delta \phi / \Delta E_{pk} \). We see that the smallest absolute value of \( \Phi_0 \) is limited by the minimum energy fluence, which allows one to fit spectra (about 1 MeV cm\(^{-2}\)) from Table 1 and the energy window of BATSE (max \( E_{pk} \approx 1870 \) keV). There are no such limitations on the high side of this distribution, since \( \Delta E_{pk} \) can be arbitrarily small and \( \Delta \phi \) is only limited by nature.

3.2. Testing the Invariance of \( \Phi_0 \) among Pulses within Bursts

LK96 reported that the decay constant \( \Phi_0^{Lk} \) sometimes remains fixed from pulse to pulse within some bursts. Such behavior would hint at a regenerative source rather than a single catastrophic event (such as Mészáros & Rees 1993).

However, the intrinsically narrow distribution of decay constants mentioned above and the relatively large confidence regions for each pulse's value of \( \Phi_0 \) suggest that many bursts would appear to have an invariant decay constant merely by chance.

As done earlier with a larger, but less reliable, set of pulses (Crider, Liang, & Preece 1998b), we calculated three statistics for each multipulse burst to test the invariance of the \( E_{pk} \) fluence decay constant. We compared two of each burst's \( M \) pulses at a time using the statistic

\[
X_{ij}^2 = \frac{[\Phi_0(i) - \Phi_0(j)]^2}{\sigma_{\Phi_0(i)}^2 + \sigma_{\Phi_0(j)}^2},
\]
and then distilled the comparisons within each burst into a single statistic to represent that burst. These statistics are defined in Table 2. Each is tailored for different null hypotheses. The statistic $G_1$ tests if at least two pulses in a burst are similar (and thus "invariant"), while $G_2$ tests if all the pulses have a similar decay constant. $G_3$ tests for either a single good pairing or several moderately close pairings. We believe that this last statistic is the most reasonable for testing our results, since it does not require that all pulses decay at the same rate (as $G_2$ does), but also does not discard information about multiple pulses repeating (as $G_1$ does). Finally, we calculated a table of probabilities $P(G, M)$ for our goodness-of-fit statistics $G$ based on a simple Monte Carlo simulation. We created synthetic bursts with pulse decay parameters randomly sampled from the observed distributions of $\Phi_0$ and $\sigma_{\Phi_0}/\Phi_0$. To avoid any bias that intrinsic invariances would have on these distributions, we created them using only one pulse from each burst. The sample of bursts in this study has fewer bursts than previous works, and hence has fewer bursts with more than one pulse. The three versions of the $G$ statistic defined above are equivalent when only two pulses appear in a burst. Thus for this sample, with only three of the nine multipulse bursts having more than two pulses, these statistics are nearly equivalent. The high probability that the observed repetitions occurred by coincidence leads us to conclude that pulse decays are not invariant from pulse to pulse within bursts. Instead, we suggest that the distribution of values $\Phi_0$ seen in all bursts is narrow enough that an apparent invariance of $\Phi_0$ is inevitable in some bursts. We came to the same conclusion when examining $\Phi_0$ (Crider et al. 1998b).

### 4. Discussion

Out of the 26 bursts to which we could fit a time-evolving Band et al. (1993) GRB function, all contain at least one pulse consistent with a linear decay of $E_{pk}$ with respect to energy fluence. Of the 41 pulses in these bursts, all are consistent ($Q > 0.001$; Press et al. 1992) with this decay pattern. This is also true when we fitted the LK96 exponential decay of $E_{pk}$ with respect to photon fluence. Besides LK96, other quantitative spectral evolution trends have been reported for our goodness-of-fit statistics $G$.

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**Table 2**

| Definition of $G_a$                                                                 | $P(G_{\text{random}} < G_{\text{estimated}})$ |
|----------------------------------------------------------------------------------|-----------------------------------------------|
| $G_1 \equiv \min X_{ij}^2$                                                       | 0.84                                          |
| $G_2 \equiv \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} X_{ij}^2$                         | 0.49                                          |
| $G_3 \equiv \prod_{i=1}^{M-1} \prod_{j=i+1}^{M} X_{ij}^2$                      | 0.90                                          |

* These probabilities are high enough to suggest that any invariance seen in the data is purely coincidental.
for GRBs. The averaged temporal and spectral evolution for 32 bright GRBs has been calculated by Fenimore (1997). The averaged photon flux evolution can be described as both rising and decaying linearly with time. The hardness, as measured by $E_{pk}$ with $\alpha$ and $\beta$ held fixed, also appears to decay linearly with time during the averaged burst [$E_{pk} = E_{pk(0)}(1 - t/t_0)$]. This is clearly not representative of all bursts since the evolution of $E_{pk}$ in bursts is often complex (Ford et al. 1995; Liang & Kargatis 1996). These trends possibly reflect the physics dictating the envelope of emission. The fact that LK96 found the $E_{pk}$ fluence trend in many mingled pulses may result from the fact that the burst envelope also evolves in this manner.

Since the hardness of this envelope appears to decay more slowly than the hardness during the pulses we observe, we might not expect to see this trend in our pulses. However, the degree of confidence of $E_{pk}$ in our fits, coupled with the fact that energy fluence is often linear in time, makes the observations of many bursts possibly consistent ($Q > 0.001$) with this decay law. Testing the distribution of $Q$ values as we did in Figure 3, we find a probability $P = 0.001$ that the pulses are realizations of linear $E_{pk}$-time trend, compared to $P = 0.18$ for the linear $E_{pk}$-fluence trend. While the linear $E_{pk}$-time relation does not seem to describe individual pulses as well as the $E_{pk}$-fluence relation, the results are not conclusive.

More pulses are clearly needed if one is to discriminate between any two time-dependent spectral functions. One could simply wait for bursts to occur or for a more sensitive instrument to be built. However, it may be possible to increase the number of fittable pulses using the existing BATSE database. Fitting a time-dependent spectral function directly to higher time resolution data (or time-tagged event data) greatly reduces the number of required fit parameters. Another approach may be to analytically integrate the time-dependent spectral function and fit that to integrated spectra, as has been done by Ryde & Svensson (1999). By increasing the number of pulses, it will become possible to make more definitive statements about the evolution of prompt GRB emission and how it relates to the GRB afterglow.

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