EVOLUTION OF THE LOW-ENERGY PHOTON SPECTRA IN GAMMA-RAY BURSTS

A. CRIDER, E. P. LIANG, AND I. A. SMITH
Department of Space Physics and Astronomy, 6100 South Main, Rice University, Houston, TX 77005-1892
R. D. PREECE, M. S. BRIGGS, G. N. PENDLETON, AND W. S. PACIESAS
Department of Physics, University of Alabama at Huntsville, Huntsville, AL 35899
AND
D. L. BAND AND J. L. MATTESON
Center for Astrophysics and Space Sciences 0111, University of California at San Diego, La Jolla, CA 92093
Received 1996 November 18; accepted 1997 January 22

ABSTRACT

We report evidence that the asymptotic low-energy power-law slope $\alpha$ (below the spectral break) of BATSE gamma-ray burst (GRB) photon spectra evolves with time rather than remaining constant. We find that a high degree of positive correlation exists between the time-resolved spectral break energy $E_{\text{pk}}$ and $\alpha$. In samples of 18 “hard-to-soft” and 12 “tracking” pulses, evolution of $\alpha$ was found to correlate with that of the spectral break energy $E_{\text{pk}}$ at the 99.7% and 98% confidence levels, respectively. We also find that in the flux rise phase of hard-to-soft pulses, the mean value of $\alpha$ is often positive, and in some bursts the maximum value of $\alpha$ is consistent with a value $\alpha > 0$. BATSE burst 3B 910927, for example, has an $\alpha_{\text{max}}$ equal to $1.6 \pm 0.3$. These findings challenge GRB spectral models in which $\alpha$ must be negative or remain constant.

Subject headings: gamma-ray bursts—observations—methods: statistical

1. INTRODUCTION

Studies of gamma-ray burst (GRB) spectral evolution have recently begun to uncover trends that may constrain the emission mechanisms. Earlier reports on spectral evolution focused solely 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 $E_{\text{pk}}$ (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 typically 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 soft” trend (Norris et al. 1986), decreasing monotonically

The recent discovery that $E_{\text{pk}}$ often decays exponentially in bright, long, smooth BATSE GRB pulses as a function of photon fluence $\Phi$ provides a new constraint for emission models (Liang & Kargatis 1996), and the fact that the decay constant $\Phi_0$ often remains fixed from pulse to pulse within a single burst hints at a regenerative source rather than a single catastrophic event (such as described in Mészaros & Rees 1993). However, that study concentrated only on the evolution of $E_{\text{pk}}$. To further explore the origin of the spectral break, we begin the analysis of two additional parameters in the spectral evolution, the asymptotic low-energy power-law slope $\alpha$ below $E_{\text{pk}}$ and the high-energy power-law slope $\beta$ above $E_{\text{pk}}$, as they are defined in the Band et al. (1993) GRB spectral function

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

where $A$ is the amplitude (in photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$) and $E_0 = E_{\text{pk}}/(2 + \alpha)$. We note that $\alpha$ is not the maximum low-energy slope of the GRB function within the detector range, but is the asymptotic limit of the slope if extrapolated to arbitrarily low energies. The observed values and variability of all three parameters are crucial in evaluating the wide field of proposed models of GRB emission. For example, many models of the spectral break require $\alpha$ to stay constant (e.g., self-absorption) or to have negative values (e.g., $-2/3$; Katz 1994; Tavani 1996), even when $E_{\text{pk}}$ evolves. In our study, we find that there are hints that $\alpha$ decreases over the course of some bursts, as suggested by COMPTEL results (Hanlon et al. 1995), and stays constant in others. In this Letter, we focus on the evolution of $\alpha$ and save the discussion of $\beta$ for future work (Preece et al. 1997).

2. SPECTRAL EVOLUTION PATTERNS

To determine the evolution of the spectral shape of GRBs, we examine high-energy resolution data collected from the BATSE large-area detectors (LADs) on board the Compton Gamma-Ray Observatory (Fishman et al. 1989). We select bursts that have a BATSE fluence (28–1800 keV) >2 × 10$^{-3}$ ergs cm$^{-2}$, which results in a set of 79 bursts. The counts from the LAD most normal to the line of sight of each burst are background-subtracted and binned into time intervals each with a S/N of ~45 within the 28 to 1800 keV range. We fit the Band et al. (1993) GRB function to each interval and thus obtain the time evolution of the three Band et al. parameters that define the spectral shape.

 Figures 1 and 2 show sample BATSE bursts (3B) 910927, 911031, 920525, and 931126, displayed for illustrative purposes. (See Liang & Kargatis 1996 for $E_{\text{pk}}$-fluence diagrams for 911031, 920525, and 931126.) The spectra show that for these bursts, $\alpha$ generally rises and falls with the instantaneous $E_{\text{pk}}$, though exact correlation between the two parameters is not
evident. In Figure 1, $\beta$ stays relatively constant throughout most of the burst, while $E_{pk}$ and $\alpha$ both steadily decrease.

To determine if $\alpha$ does indeed evolve in time in a majority of bursts, we fit a zeroth- ($M = 0$) and first-order ($M = 1$) polynomial to the $\alpha$ evolution in each burst. Assuming a null hypothesis in which $\alpha$ is constant during a burst and the time-resolved values of $\alpha$ are normally distributed about the mean, we expect the value $D = X_M^2$, where $X_M^2$ is a statistic with $1$ degree of freedom (Eadie et al. 1971). We calculate for each burst the probability $Q$ of randomly drawing a value greater than or equal to $X_M^2$. We observe that $46$ have a $Q$ below our acceptable cutoff of $0.001$. We conclude that a majority of bursts in our sample show evidence for at least a first-order trend in $\alpha$.

The four sample bursts above suggest that evolution of $\alpha$ mimics that of $E_{pk}$. To see if this occurs in other bursts, we attempt to disprove the null hypothesis that $\alpha$ is uncorrelated with $E_{pk}$. To test the degree of correlation between $\alpha$ and $E_{pk}$, in each of our $79$ bursts we compute the Spearman rank correlation $\rho$ (Press et al. 1992). For each burst with a positive $\rho$, we find the probability $P_+$ of randomly drawing a value of $\rho$ that high or higher assuming no correlation exists. For each burst with a negative $\rho$, we find the probability $P_-$ of randomly drawing a value of $\rho$ that low or lower assuming no anticorrelation. The division of the bursts in this way precludes the inclusion of systematic anticorrelations, which could occur given the negative covariance between $\alpha$ and $E_{pk}$ and the observed shape of our $\chi^2$ minimum contours. We next calculate the Kolmogorov-Smirnov (K-S) $D$ statistic between the measured distribution of $P_+$ or $P_-$ and the distribution one would expect if no correlation or anticorrelation existed. We find $D = 0.45$ for the $47$ positively correlated bursts. The likelihood of this value, assuming no intrinsic correlation, is $2 \times 10^{-8}$. The bursts showing negative correlation, which suffer from systematics described above, are still consistent (likelihood $= 0.04$) with a noncorrelation hypothesis. From this we conclude that a positive correlation exists between $\alpha$ and $E_{pk}$ in at least some subset of bursts.

To determine if this relation exists in hard-to-soft or tracking pulses, we select $18$ pulses that we determine to be clearly hard-to-soft and $12$ pulses that are clearly tracking from the more than $240$ pulses within our $79$ bursts. Pulses are included in the hard-to-soft category if the maximum $E_{pk}$ occurs before the flux peak and is greater than $E_{pk}$ at the flux peak by at least $\alpha E_{pk}$. Pulses are tracking if the rise and fall of $E_{pk}$ coincides with those of the flux to within $1$ time bin (typically $\sim 1/2$ s) and if the rise lasts at least $3$ time bins. We do not pretend that all

![FIG. 1.—Evolution of the Band et al. (1993) GRB spectral function for 3B 910927. Each line is marked with the time (in s) corresponding to the beginning of the time bin. Note that a typical statistical $\beta$ error $\sigma_\beta \approx 0.4$. The nearly linear decay of $\alpha$ throughout this burst suggests that the early high values of $\alpha$ are not statistical fluctuations. However, this burst is still consistent with $\alpha \leq +1$. Upper inset: Evolution of $E_{pk}$ (squares, logarithmic scale) and photon flux (histogram, linear scale) with respect to fluence. Lower inset: Evolution of $\alpha$ (circles) and photon flux (histogram) with respect to time. Error bars represent $1 \sigma$ confidence level.

![FIG. 2.—Band et al. (1993) $\alpha$ (circles), linear $E_{pk}$ (diamonds), and photon flux (histogram) evolution in time for 3B 911031 [GRB 973], 3B 920525 [GRB 1625], and 3B 931126 [GRB 2661]. These three bursts suggest that $\alpha$ evolves in a manner similar to $E_{pk}$. Error bars represent a $1 \sigma$ confidence region. The vertical dimensions of the diamonds represent a $1 \sigma$ confidence region for $E_{pk}$ and the horizontal dimensions represent the durations of the time bins. (See Liang & Kargatis 1996 for $E_{pk}$ vs. fluence of these bursts with $\alpha$ and $\beta$ fixed to the time-integrated value.)
pulses fall into one of these two categories, but instead treat them as extreme examples in a continuum of evolutionary patterns. Following the same analysis described above on these smaller populations, in cases with positive $\beta$ we find the likelihood of these observed values of $\beta$, assuming no intrinsic correlations, is 0.003 ($D = 0.46$) for the hard-to-soft pulses and 0.02 ($D = 0.45$) for the tracking pulses. In contrast, while four of the 18 hard-to-soft pulses and six of the 12 tracking pulses were anticorrelated, the likelihood of these randomly occurring was 0.78 for the hard-to-soft cases and 0.29 for the tracking cases, values consistent with the null hypothesis of no anticorrelation. In Figure 3, we compare the cumulative distributions of the 14 hard-to-soft and six tracking pulses that are positively correlated to that of the 47 positively correlated bursts. We find that both distributions of pulses are similar to the burst distribution that implies an $E_{pk}$-$\alpha$ correlation. We conclude from this statistical evidence that for hard-to-soft and, with less confidence, for tracking pulses the asymptotic low-energy power-law slope $\alpha$ evolves in a manner similar to $E_{pk}$.

3. LOW-ENERGY POWER INDEX IN THE RISE PHASE OF PULSES

Assuming that $\alpha$ mimics $E_{pk}$, it follows that $\alpha$ decreases monotonically for hard-to-soft pulses, whereas it increases during the rise phase of tracking pulses. We compare the averaged values of $\alpha$ during the rise phase for these two groups and find that those in hard-to-soft pulses are significantly higher. While none of the 12 tracking pulses has an average $\alpha_{rise} > 0$, seven of the 18 hard-to-soft pulses have an average $\alpha_{rise} > 0$ (see Fig. 4). A K-S test between the two distributions gives a value of $D = 0.56$, implying a probability of 0.014 that these two samples were randomly taken from the same distribution.

We next examine the highest value of $\alpha_{max}$, that occurs in our time-resolved spectra. This value serves as a valuable test for GRB emission models. In Figure 5, we provide the distribution of $\alpha_{max}$ found in each of our 79 bursts. Only a few bursts examined so far suggest that their maximum $\alpha$ may be greater than +1. As indicated in Figure 5, all of the bursts with $\alpha_{max}$ greater than +1 have large statistical uncertainties. The nearly linear decrease of $\alpha$ with respect to time in 3B 910927 suggests that its relatively high $\alpha_{max}$ of $1.6 \pm 0.3$, found using data from the LAD most normal to the burst, is not merely a statistical fluctuation (see Fig. 1). Further examination reveals, however, that this burst is still consistent with $\alpha \leq +1$ for its duration. In addition, jointly fitting the data from the two LADs most normal to the burst reduces $\alpha_{max}$ to $1.03 \pm 0.15$.

We also note that fitting 3B 910927 with a broken power law instead of the Band et al. (1993) GRB function gives the same linear decrease of the low-energy power-law slope $\gamma_1$ with respect to time and reduced-$\chi^2$ values comparable to those of the Band et al. GRB function fit. However, $\gamma_1 < 0$ throughout the burst, a value of the low-energy slope lower than that found using the Band et al. GRB function. If the GRB function better represents the underlying physics, then this difference would be expected. The parameter $\gamma_1$ measures the effective average slope below $E_{pk}$, whereas $\alpha$ measures asymptotic value, allowing for the curvature of the exponential function.

4. SUMMARY AND DISCUSSION

We establish that the asymptotic low-energy power-law slope, represented by the Band et al. (1993) parameter $\alpha$, evolves with time rather than remaining fixed to its time-integrated value in 58% of the bursts in our sample. We find strong evidence that a correlation between the parameters $E_{pk}$ and $\alpha$ exists in the time-resolved spectra of some BATSE GRBs, and, with slightly less confidence, we determine that this correlation exists in both hard-to-soft and tracking pulses. We also find that in ~40% of the hard-to-soft pulses, the average value of $\alpha$ during the flux rise phase is $>0$, while for tracking pulses the average $\alpha$ is always $\leq 0$. For 3B 910927, using data from only the LAD receiving the most counts, we determine a maximum value of $\alpha = 1.6 \pm 0.3$. However, we cannot yet prove that $\alpha_{max} > 1$ in any burst examined so far, because of the broadness of the $\chi^2$ minimum.

GRB spectral breaks can in principle be caused by synchrotron emission with a low-energy cutoff or self-absorption. However, in the former case, $\alpha$ is always less than or equal to $-2/3$ (Katz 1994; Tavani 1996) with no evolution. Such a low and constant $\alpha$ is inconsistent with many observed BATSE bursts. For instance, in 3B 910927 fitting the time bin in which $\alpha$ is maximum with an $\alpha$ fixed to $-2/3$ results in a $Q$ of $1.5 \times 10^{-11}$, much lower the $Q = 0.35$ obtained when $\alpha$ is a free parameter. In the case of self-absorption, $\alpha$ could go as high as +1 (thermal) or +1.5 (nonthermal, power-law) (Rybicki & Lightman 1979). But again, in such models, $\alpha$ cannot evolve.
with time, only $E_{\text{pk}}$ (which would be interpreted as the self-absorption frequency) can. Hence, these conventional interpretations of the spectral break of GRB continua can be ruled out by our results. Implications of our results on various cosmological scenarios (e.g., Shaviv 1996) remain to be investigated.

The spectral breaks can also be caused by multiple Compton scattering (Fenimore et al. 1982; Liang & Kargatis 1996). In this case, the decay of $\alpha$ in hard-to-soft pulses can be interpreted as the Thomson thinning of a Comptonizing plasma (Liang et al. 1997) and the initial $\alpha$ can in principle go as high as $+2$, because in the limit $\tau_r$ (Thomson depth) $\rightarrow \infty$ one would expect a Wien peak. However, several factors make it difficult to clearly measure an early low-energy power law $\sim +2$ even if the spectral break is related to a Wien peak. The most obvious problem is that the highest $\tau_r$ would occur earliest in a hard-to-soft pulse, when the flux is the lowest, so that fitting a precise spectral model becomes difficult. Another problem is that even if the true GRB spectral break is Wien-like, if one had used a function other than the Band et al. (1993) function (e.g., broken power law) or simply measured the slope within the BATSE range, one could get a slope flatter than $+2$. This is evident in Figure 5, in which the maximum slope for the same set of bursts appears to only approach $+1$ while $\alpha_{\text{max}}$ appears to approach $+2$. This is because the exponential curvature depresses the apparent slope relative to the asymptotic power law of the Wien function. Also important is that the Band et al. GRB function does not take into account the soft X-ray upturn expected from saturated Comptonization of soft photons (Rybicki & Lightman 1979; Liang et al. 1997). If the lower boundary of the fitting energy window is below the relative minimum in the saturated Comptonization photon spectrum (Pozdnyakov, Sobol, & Syunyaev 1983), any fitted, low-energy power law, such as the Band et al. (1993) GRB function, will be flatter than the true slope for the Wien peak. Preliminary results show that moving the lower energy cutoff of the fitting region allows one to get a higher $\alpha$. However, the uncertainty in $\alpha$ increases when reducing the size of the fitting window and thus the higher value of $\alpha$ may be misleading. Evidence for the X-ray upturns in the low-energy spectra have been found by Preece et al. (1996), who found positive residuals between the BATSE data and their fitted Band et al. (1993) GRB functions in many bursts. However, further analysis of time-resolved, low-energy GRB spectra is needed before a model involving saturated Comptonization can be tested.

A. C. thanks NASA-MSFC for the Graduate Student Research Program fellowship and E. E. Fenimore for useful discussions. This work is supported by NASA grant NAG5-1515.

REFERENCES

Band, D., et al. 1993, ApJ, 413, 281
Eadie, W. T., Drijard, D., James, F. E., Roos, M., & Sadoulet, B. 1971, Statistical Methods in Experimental Physics (Amsterdam: North-Holland)
Fenimore, E. E., Klebesadel, R. W., Laros, J. G., & Stockdale, R. E. 1982, Nature, 297, 665
Fishman, G. J., et al. 1989, Proc. GRO Science Workshop, 2-39
Ford, E. A., et al. 1995, ApJ, 439, 307
Golenetskii, S. V., Mazets, E. P., Aptekar, R. L., & Il'inskii, V. N. 1983, Nature, 306, 451
Hanlon, L. O., Bennett, K., Williams, O. R., Winkler, C., & Preece, R. D. 1995, Ap&SS, 231, 157
Katz, J. I. 1994, ApJ, 432, L107
Liang, E. P., & Kargatis, V. E. 1996, Nature, 381, 49
Liang, E. P., Smith, I. A., Kasunose, M., & Crider, A. 1997, ApJ, this issue
Meszaros, P., & Rees, M. J. 1993, ApJ, 405, 278
Norris, J. P., et al. 1986, ApJ, 301, 213
Preece, R. D., et al. 1996, ApJ, 473, 310
Preece, R. D., et al. 1997, in preparation
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C (2d ed.; Cambridge: Cambridge Univ. Press)
Rybicki, G. B., & Lightman, A. P. 1979; Radiative Processes in Astrophysics (New York: Wiley)
Shaviv, N. J. 1996, Ph.D. thesis, Israel Inst. Technology
Tavani, M. 1996, ApJ, 466, 768