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GAMMA-RAY BURST PEAK DURATION AS A FUNCTION OF ENERGY

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ABSTRACT

Gamma-ray burst time histories often consist of many peaks. These peaks tend to be narrower at higher energy. If gamma-ray bursts are cosmological, the energy dependence of gamma-ray burst timescales must be understood in order to correct the timescale dependence due to the expansion of the universe. By using the average autocorrelation function and the average pulse width, we show that the narrowing with energy follows, quite well, a power law. The power-law index is ~ -0.4. This is the first quantitative relationship between temporal and spectral structure in gamma-ray bursts. It is unclear what physics causes this relationship. The average autocorrelation has a universal shape such that one energy range scales linearly with time into all other energy ranges. This shape is approximately the sum of two exponentials.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The Burst and Transient Experiment (BATSE) on the *Compton Gamma Ray Observatory* (*CGRO*) has deepened the mystery of gamma-ray bursts (GRBs) rather than solving it. GRBs appear to be isotropic on the sky, yet there is a dearth of faint events compared to the brightest events (Meegan et al. 1992). The two most likely explanations for this situation are either that the bursts are at cosmological distances (and the dearth of events is due to effects associated with the expansion of the universe) or that the events are from an extended halo about our Galaxy (and the dearth of events is due to a decrease in the density of neutron stars in the halo). If cosmological, the expansion of the universe shifts the photon energies by a factor of $1/(1 + z)$, where z is the redshift and stretches the temporal structure by a factor of $1 + z$. Indeed, time dilation has been claimed on all timescales within GRBs (Norris et al. 1994, 1995a; Davis et al. 1994). Norris et al. (1994, 1995a) interpret the factor-of-2 dilation as consistent with the GRB log N–log P distribution, although perhaps with some evolution. Fenimore & Bloom (1995) contend that it is not consistent when one includes all the factors relating distance to time dilation. One key factor involves the tendency for peaks in GRB time histories to be narrower at higher energy. Fishman et al. (1992) noted that individual peaks frequently are narrower and better defined at higher energies. Link, Epstein, & Priedhorsky (1993) showed that this is a prevalent property of most bursts. In this Letter we show that there is a well-defined relationship for the average width of peaks as a function of energy. We will show that the average autocorrelation function for many bursts is a very well behaved function with a shape that is universal. Heuristically, an autocorrelation measures the average relative intensity between points in the time history that are separated by an amount of time called the lag. As such, it can be used to detect changes in timescales that might be associated with the expansion of the universe or to measure the average peak width as a function of energy. The average autocorrelation is fairly immune to systematic effects such as the identification of the highest peak. The noise is explicitly accounted for by calculating the expected autocorrelation given the noise level. The average autocorrelation is similar to the aligned peak tests in that the peak of each burst is used as a fiducial to form an average and is sensitive to timescales the order of a few seconds. It is roughly equivalent to aligning most of the peaks in a burst rather than just the highest.

2. INSTRUMENTATION

The BATSE experiment on *CGRO* uses eight large-area detectors (LADs) to locate and study GRBs over a large dynamic range (see Fishman et al. 1992). For the purposes of this study, we will use the four channel triggered data. This consists of the counts in four broad energy bins labeled 1 for 25–57 keV, 2 for 57–115 keV, 3 for 115–320 keV, and 4 for above 320 keV, which is effectively 320–1000 keV. A data set labeled 1+2 combines 1 and 2 together to effectively create a 25–115 keV channel. A memory records $\sim$2 s of data before the trigger, and the duration of the recorded data after the trigger is $\sim$240 s. The time resolution for this data is 0.064 s. In Norris et al. (1994), the period prior to the trigger is augmented by rebinning the continuously available 1.024 s samples into 0.064 s samples. This extends the pretrigger by $\sim$16 s.

We will use the same data set as used by Norris et al. (1994) including the augmented pretrigger. Bursts were assigned by Norris et al. (1994) to a brightness class based on the largest net count rate in 0.064 s samples in channel 1+2+3+4. Those bursts with count rates between 18,000 and 250,000 counts s^{-1} are called "bright" bursts, those with counts rates between 2400 and 4500 counts s^{-1} are "dim," and those with count rates between 1400 and 2400 are called "dimmest." (Events with an intermediate count rate are not used because the time dilation effects are largest for well-separated classes.) Short events (defined here and in Norris et al. 1994 to have durations less than 1.5 s) were excluded from the study. In this Letter, we seek the intrinsic variation with energy of the width of the temporal peaks. We use only the bright events to avoid potential effects due to different distances including time dilation from the expansion of the universe. Even if GRBs come from cosmological distances, under the standard candle assumption, these events are all from approximately the same distance and therefore have the same stretching because of the expansion of the universe. There were 45 usable events in the bright class.

3. THE AUTOCORRELATION FUNCTION

The autocorrelation function for GRBs was investigated by Link et al. (1993), where it was shown that timescales are almost always shorter at higher energies. Following Link et al., let m_i be the observed gross counts in discretely sampled data in n bins of equal size ΔT ranging from $-n\Delta T/2$ to $+n\Delta T/2$ about the largest peak in the GRB time history. Here m_i is number of counts, so it follows Poisson statistics. Let b_i be the corresponding background counts. We determined the background by a linear fit to regions before and after the bursts where it was judged by eye to be inactive. The net counts are $c_i = m_i - b_i$, and the estimate of the true autocorrelation as a function of the lag, $\tau = j\Delta T$, is

$$A(\tau) = \sum_{i=-n/2}^{n/2} \frac{c_{i+j}c_i}{A_0}, \quad -n/2 < j < n/2 \qquad (1)$$

and $A(\tau) = 1$ if $j = 0$. Here, c_{i+j} is zero if $i + j > n/2$ or $i + j < -n/2$. When studying individual events (as Link et al. 1993 did), one can always use the entire time history. We average many events together and must use them in a uniform manner. This requires us to select the duration to use. If we selected a very short duration, then the autocorrelation is not sensitive to time stretching (a flat-topped burst exceeding the selected duration would show no difference in the autocorrelation). If we selected a very large duration, then there would be many instances when bursts would have to be left out of the averaging because the peak occurs within $\pm\Delta T/2$ of the ends of the data such that c_{i+j} is not defined for part of the needed range. Although bursts can be very long, usually emission more than a few seconds away from the largest peak contributes only a little to the autocorrelation function. We have found only small differences for all $n\Delta T > 8$ s and have used $n\Delta t = 16$ s throughout this Letter. By definition, the autocorrelation is symmetric, $A(\tau) = A(-\tau)$. The normalization, A_0, is

$$A_0 = \sum_{i=-n/2}^{n/2} c_i^2 - m_i\,. \qquad (2)$$

An autocorrelation without normalization would have a large peak at $\tau = 0$, where all the noise adds coherently, and would be count rate dependent at $\tau \neq 0$. The $-m_i$ term in equation (2) normalizes the autocorrelation to that expected without noise. To fit functions to the observed autocorrelations, we require a measure of its uncertainty. The terms of $A(\tau)$ are not statistically independent. However, our use of the uncertainty is only to obtain a relative goodness of fit. In fact, each term of the variance on $A(\tau)$ will be approximately the same, so its exact value is not important. The variance of the numerator of equation (1) is

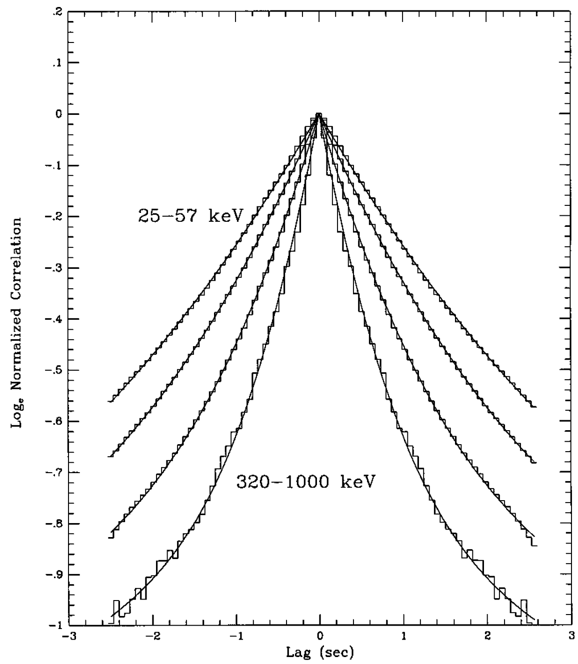

FIG. 1.—Average autocorrelation of 45 bright BATSE gamma-ray bursts in four energy channels. At higher energies, gamma-ray bursts have shorter timescales. The solid curves are fits of the sum of two exponentials to the autocorrelation histograms.

$$\sigma^2_{c*cj} = \sum_{i=-n/2}^{n/2} c_i^2|c_{i+j}| + |c_i|c_{i+j}^2\,. \qquad (3)$$

(We assume that the variance propagated from the background is small because the background is based on much more data than the individual points.) The variance on the normalization is

$$\sigma^2_{A_0} = \sum_{i=-n/2}^{n/2} 4c_i^3 + m_i\,. \qquad (4)$$

Combining equations (3) and (4) gives the variance on the jth term of the autocorrelation:

$$\sigma^2_{A(j\Delta T)} = \frac{\sigma^2_{c*cj}}{A_0^2} + \frac{A^2(j\Delta T)}{A_0^2}\sigma^2_{A_0}\,. \qquad (5)$$

The average of a fair number of GRB autocorrelations is quite stable and shows only a small variation. Let $\bar{A}(i, \tau)$ be the average autocorrelation for the ith channel or combination of channels. Figure 1 shows the average of the bright events for the four channels of the LAD data, that is, $\bar{A}(i, \tau) = \Sigma_{k=1}^{N_B} A_k(i, \tau)/N_B$, where N_B is the number of bright events (45) and k denotes different bursts. The normalization of each autocorrelation is such that each burst contributes equally to the average autocorrelation independent of its brightness. Note how clear the energy dependency is in Figure 1. Figure 1 is semilog, and the curves appear nearly as straight lines so the shape of the autocorrelation is approximately an exponential.

Each energy channel is nearly an exact time-stretched version of the others. We define $S_{i,j}$ to be the best-fit factor that scales

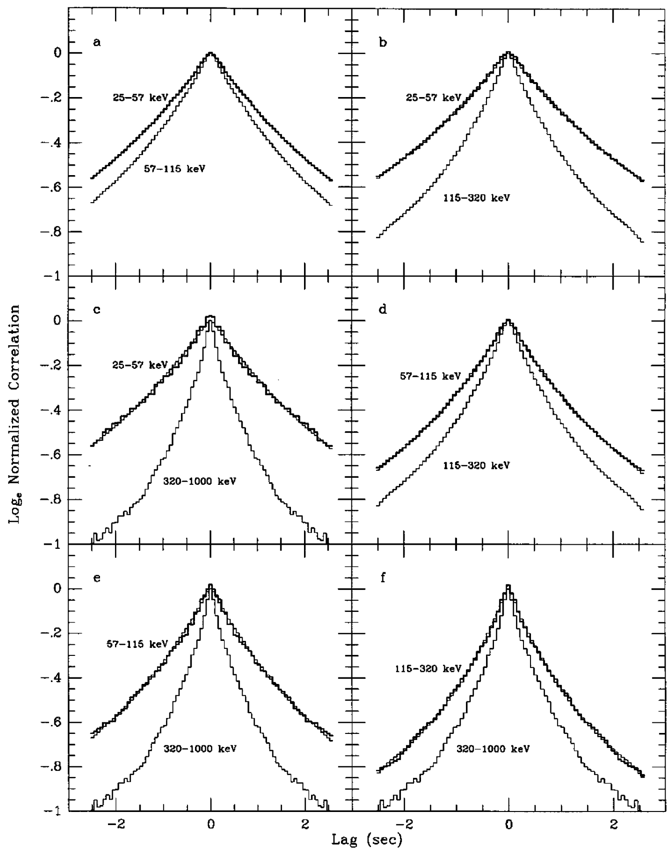

FIG. 2.—Comparisons of pairs of energy channels for the *BATSE* bright events. Each panel shows the average autocorrelation for two energy channels from the BATSE LAD data. The bold histogram is a best-fit, time-stretched version of the narrower (higher energy) channel fit to the broader (lower energy) channel. The average autocorrelation apparently has a universal shape which is approximately exponential.

$\bar{A}(i, \tau)$ into $\bar{A}(j, \tau)$. It is found by minimizing

$$\chi^2 = \sum_{l=1}^{m} \frac{[\bar{A}(j, l\Delta T) - \lambda_{ij}\bar{A}(i,S_{i,j}l\Delta T)]^2}{\sigma^2_{\bar{A}(j,l\Delta T)} + \sigma^2_{\bar{A}(i,lS_{i,j}\Delta T)}} . \qquad (6)$$

Here $m\Delta T$ is the range of lags that is used in the fit. This range is set by where the functions are well defined. The autocorrelation of the highest energy channel begins to have significant noise at ~2.5 s (see Fig. 1) so we have used $m\Delta T = 2.5$ s. Since $A(\tau)$ is symmetric, nothing is gained by including negative lags.

In each panel of Figure 2, we show the average autocorrelation for two channels. For example, in Figure 2*a*, we show $\bar{A}(1, \tau)$ (i.e., 25–57 keV) and $\bar{A}(2, \tau)$ (i.e., 57–115 keV). Also shown as a bold curve is the time-stretched autocorrelation of the higher energy channel that best fits the lower energy channel [e.g., the bold curve in Fig. 2*a* is $\lambda_{21}\bar{A}(2,S_{2,1}\tau)$]. The overall scaling ($\lambda$) is always very near unity. Note, for example, in Figure 2*c* that the bold curve slightly exceeds unity at $\tau = 0$. For energy channels with poorer statistics, the uncertainty of the normalization is reflected in $\sigma^2_{\bar{A}}$, which is nearly constant as a function of τ because $m\Delta T$ (2.5 s) is much less than $n\Delta T$ (16 s). The goodness-of-fit parameter in equation (6) will not follow the χ^2 statistic because the points are not independent. The purpose of $\sigma^2_{\bar{A}}$ is to balance the uncertainty in the overall scale factor (λ) with the uncertainty in the time stretching (S).

Figure 2 demonstrates that the average autocorrelation has a universal shape (but different time stretching) for all energies. Note how well the time-stretched higher energy autocorrelation always agrees with the broader (lower energy) autocorrelation. Even the highest energy range (320–1000 keV), which showed a deviation from an exponential in Figure 1, scales exactly into the lower energy autocorrelations.

The curves in Figure 1 are not pure exponentials; there is a slight curve to the histograms. We have tried to fit a variety of functions to the histograms. A single exponential ($\exp^{-\tau/\tau_0}$) fits poorly, especially the higher energy channels. A function such as $\exp^{a\tau^2+b\tau}$ fits the lower energy channels well but not the higher energy channels. Although not unique, the most successful function that we tried is a sum of two exponentials:

$$\bar{A}(i, \tau) = \beta_i \exp^{-|\tau|/\alpha_{i1}} + (1 - \beta_i) \exp^{-|\tau|/\alpha_{i2}} , \qquad (7)$$

where i denotes the four energy channels. To determine the free parameters in equation (7), we minimize

$$\chi^2 = \sum_{j=1}^{n/2} [\bar{A}(i,j\Delta T) - \beta_i \exp^{-|\tau|/\alpha_{i1}} - (1 - \beta_i) \exp^{-|\tau|/\alpha_{i2}}]^2 . \qquad (8)$$

The parameters α_{i1} and α_{i2} are found by searching the parameter space, and β_i is found analytically from $\delta\chi^2/\delta\beta_i = 0$. The best fits are

$$\bar{A}(1,\tau) = 0.66 \exp^{-|\tau|/2.40} + 0.34 \exp^{-|\tau|/25} , \qquad (9a)$$

$$\bar{A}(2,\tau) = 0.64 \exp^{-|\tau|/1.74} + 0.36 \exp^{-|\tau|/25} , \qquad (9b)$$

$$\bar{A}(3,\tau) = 0.48 \exp^{-|\tau|/0.94} + 0.52 \exp^{-|\tau|/9.9} , \qquad (9c)$$

$$\bar{A}(4,\tau) = 0.53 \exp^{-|\tau|/0.56} + 0.47 \exp^{-|\tau|/6.5} . \qquad (9d)$$

All values of α_{i2} above 25 are equally consistent with the data. These fits are plotted as curves in Figure 1. Equation (8) does not follow the χ^2 statistic because the $\bar{A}$ terms are not independent so we cannot qualitatively evaluate the fit. However, as seen in Figure 1, the fit is excellent.

4. ENERGY DEPENDENCE OF TIMESCALE

We will characterize the energy dependence of the typical timescale in the GRB time history using two different measures: the width of $\bar{A}$ and the width of the average pulse profile (from Norris et al. 1994, 1995b). The solid triangles in Figure 3 are the width (W_{ac}) of each autocorrelation from Figure 1 as measured by where $\ln \bar{A}(\tau) = 0.5$. Since Figure 3 is log-log and the points nearly lie on a straight line, we have fitted a power law to the points. The best-fit power law is $W_{ac}(E) = 17.4E^{-0.43}$. This function is shown in Figure 3 as a solid line. This is a robust result. Using the width at other values of $\bar{A}$ gives similar results. Also, the fact that the autocorrelation function for each energy can be scaled into another and they overlap so well (Fig. 2) implies that the power law holds for more than just the point where $1n\, \bar{A}(\tau) = 0.5$ (see discussion of eq. [10]).

One thing that is not clear in our formulation is at what energy to place the points. We have placed them at the energy corresponding to the lower energy bound of the channel that they represent. The autocorrelation function is quadratic in counts (see eq. [1]), so for any particular channel, the width reflects where most of the counts are. For example, if one combines channels 3 and 4, it has effectively the same width as channel 3 only. If we were to use the midpoint of the channel,

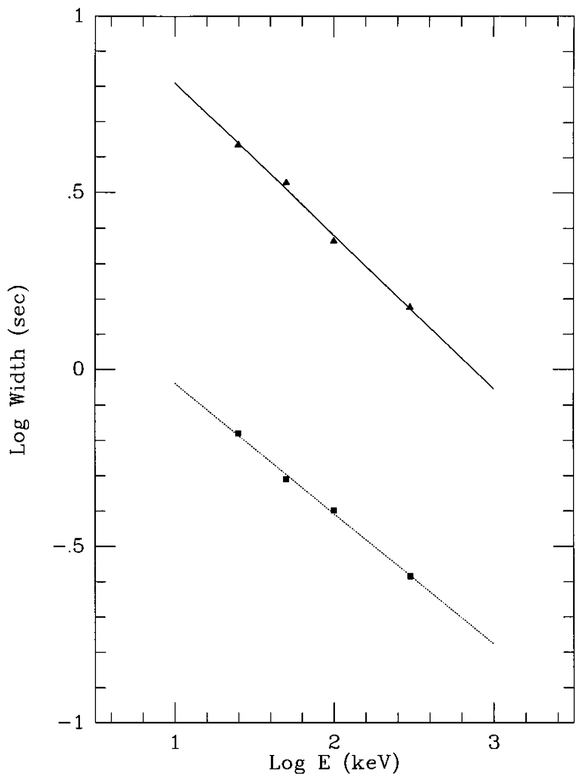

FIG. 3.—Energy dependency of the timescale as determined by the average autocorrelation and the average pulse width. The triangles are the half-width of the autocorrelation function, and the solid curve is a best-fit to the triangles. The squares are the sum of the rise and fall of the average pulse profile, and the dotted line is a best fit to it. In each case, the timescale of the temporal structure within the GRB scales as a power law of the energy with an index of ~ -0.4.

it is still a power law: $W_{ac} = 18.1E^{-0.40}$. Another possible measure of the timescale of $\bar{A}$ is how much one energy range needs to be stretched in order to map it into another energy range. This is not independent from W_{ac} but serves as another way to measure it (eq. [6] rather than eq. [1]). Using channel 1 as a baseline (i.e., if $S_{11} = 1$), $S_{21}^{-1} = 0.78$, $S_{31}^{-1} = 0.54$, and $S_{41}^{-1} = 0.33$ give how much the autocorrelations of the higher energy channels are narrower as a function of energy. Fitting the S_{i1}^{-1} points gives $S_{i1}^{-1} = 4.45E_i^{-0.46}$. A second measure of the timescale of GRBs comes from the average pulse width. Norris et al. (1994) decomposed GRB time histories into individual pulses and found the average rise and fall time scales. The widths (in seconds) of the rise/fall of the average pulse profile are 0.22/0.44, 0.17/0.32, 0.13/0.27, and 0.08/0.18 for BATSE channels 1, 2, 3, and 4, respectively. We plot in Figure 3 as squares the sum of the rise and fall times as a function of energy. Again, the energy dependence of the timescale appears to be a power law. In this case, the average pulse width is $W_{ap} = 2.1E^{-0.37}$, which is plotted in Figure 3 as a dotted line.

Another measure of the pulse width is the average full width, half-maximum (FWHM). Norris et al. (1995b) reports that the average FWHM for the four BATSE channels are 0.817, 0.616, 0.473, and 0.287 s. These widths can be fitted by a power law as well: $W_{FWHM} = 3.2E^{-0.42}$. This, too, is very robust. Norris et al. (1995b) reports the width for seven different fractions of the peak height, and all seven can be fitted with a power law.

We note that the average pulse width is much less than the width from the autocorrelation function. The individual pulses are narrower than the clusters of peaks that often determine the autocorrelation width. However, there is not a simple relationship between the two measures. For example, simulations of shot noise with pulses the order of the average pulse width produce autocorrelation functions that are much narrower than observed.

In equation (8), we fitted each energy channel separately using 12 parameters. From Figure 3, we see that the energy dependence of the timescale in GRBs is a power law. The parameters α_{i1} and α_{i2} found in equation (9) do not follow a power law. However, it is possible to have a functional form that has a power-law dependency on energy and fits within the noise. We fitted all four curves in Figure 1 with

$$\bar{A}(i,\tau) = \beta \exp^{-(|\tau|/k_1 E_i^{-\alpha})} + (1 - \beta) \exp^{-(|\tau|/k_2 E_i^{-\alpha})} . \quad (10)$$

This form accommodates the three characteristics of the average autocorrelation: it consists of two exponentials, the energy dependence scales as a power law, and the shape of one energy range scales linearly with time into all the other energy ranges. The parameters $\beta = 0.55$, $k_1 = 8.75$, $k_2 = 154$, and $\alpha = 0.45$ give an acceptable fit.

In summary, we find that the average autocorrelation of the time histories of GRBs is a universal function that can measure the timescale as a function of energy. The dependence is a power law in energy with an index that is between 0.37 and 0.46, depending on how it is measured. This is the first quantitative relationship between temporal and spectral structure in gamma-ray bursts. The energy dependence is important for two reasons. First, the shape may indicate the underlying physics responsible for the time history. For example, the subpeak's temporal width might be produced by the growth of a shock within a relativistic expanding shell in a cosmological GRB, and the power-law dependence on energy is related to how the shock converts bulk motion into gamma rays. Alternatively, the energy dependence might be related to how a disturbance propagates on the surface of a neutron star. Second, in order to interpret the time dilation due to the expansion of the universe, one must understand the energy dependence which competes with the cosmological time dilation to form the temporal width. Fenimore & Bloom (1995) include the energy dependence in the interpretation of time stretching as a function of burst brightness and conclude that the observed time dilation is not consistent with the observed log *N*–log *P* distribution (Fenimore et al. 1993) unless there is strong evolution and it is only coincidental that the log *N*–log *P* distribution shows a $-3/2$ power law.

REFERENCES

Davis, S. P., Norris, J. P., Kouveliotou, C., Fishman, G. J., Meegan, C. A., & Paciesas, W. C. 1994, in Gamma-Ray Bursts: Second Workshop Huntsville, 1993, ed. G. J. Fishman, J. J. Brainerd, & K. C. Hurley (New York: AIP), 182
Fenimore, E. E., & Bloom, J. S. 1995, ApJ, submitted
Fenimore, E. E., et al. 1993, Nature, 366, 40
Fishman, G., et al. 1992, in Gamma-Ray Bursts: Huntsville, 1991, ed. W. S. Paciesas & G. J. Fishman (New York: AIP), 13
Link, B., Epstein, R. I., & Priedhorsky, W. C. 1993, ApJ, 408, L81
Meegan, C. A., et al. 1992, Nature, 355, 143
Norris, J. P., et al. 1994, ApJ, 424, 540
———. 1995a, ApJ, 439, 542
———. 1995b, in preparation