DETECTION OF SIGNATURE CONSISTENT WITH COSMOLOGICAL TIME DILATION IN GAMMA-RAY BURSTS

J.P. Norris[(1)], R.J. Nemiroff[(1),(2)], J.D. Scargle[(3)], C. Kouveliotou[(2),(4)], G.J. Fishman[(4)], C. A. Meegan[(4)], W.S. Paciesas[(4),(5)], and J.T. Bonnell[(1),(6)]

[(1)] *NASA Goddard Space Flight Center, Greenbelt, MD 20771*
[(2)] *Universities Space Research Association*
[(3)] *NASA Ames Research Center, Moffet Field, CA 94035*
[(4)] *NASA Marshall Space Flight Center, Huntsville, AL 35812*
[(5)] *University of Alabama, Huntsville, AL 35899*
[(6)] *Computer Sciences Corporation*

In press: ApJ, 1 April 1994, ApJ, 424, 540

ABSTRACT

If gamma-ray bursters are at cosmological distances - as suggested by their isotropic distribution on the sky and by their number-intensity relation - then the burst profiles will be stretched in time, by an amount proportional to the redshift, $1 + z$. We have tested data from the Compton Gamma Ray Observatory's Burst and Transient Source Experiment (BATSE) for such time dilation. Out of 590 bursts observed by BATSE, 131 bursts were analyzed; bursts with durations shorter than 1.5 s were excluded. We used three tests to compare the timescales of bright and dim bursts, the latter, on average, being more distant than the former. Our measures of timescale are constructed to avoid selection effects arising from intensity differences by rescaling all bursts to fiducial levels of peak intensity and noise bias. (1) We found that the total rescaled count above background for the dim burst ensemble is approximately twice that for the brightest bursts - translating into longer durations for the dim bursts. (2) Wavelet-transform decompositions of the burst profiles confirmed that this dilation operates over a broad range of timescales. (3) Structure on the shortest timescales was examined using a procedure which aligns the highest peaks of profiles from which the noise has been optimally removed using a wavelet thresholding technique. In all three tests, the dim bursts are stretched by a factor of ~ 2 relative to the bright ones, over seven octaves of timescale. We calibrated the measurements by dilating synthetic bursts that approximate the temporal characteristics of bright BATSE bursts. Results are consistent with bursts at BATSE's peak-flux completeness limit being at cosmological distances corresponding to $z \sim 1$, and thus with independent cosmological interpretations of the BATSE number-intensity relation. Alternative explanations of our results, arising from the nature of physical processes in bursts, are still possible.

Subject headings: cosmology: theory - gamma rays: bursts

1. INTRODUCTION

The long-standing mystery of the nature and distances to gamma-ray burst sources might be addressable in the near future by simultaneous detection of a single burst counterpart in another waveband. Such a detection could serve as the "Rosetta Stone" of bursts, especially if the bursters are a galactic halo and/or disk population. It is less likely that counterparts at cosmological distances could be studied in quiescence, especially since some critical determinants might not be observable: the best determined burst error positions for the brightest bursts do not appear to be associated with bright galaxies (e.g., luminosity comparable to M31) or with AGNs (Fenimore et al. 1993). Instead, a good proof of cosmological origin would be multiple gravitationally lensed (temporally separated) images of a burst. A few such cases might be seen over the lifetime of the Compton Observatory, depending on the depth of a cosmological distribution (Nemiroff et al. 1993b). The cosmological origin of bursts would also be indicated by detection of galactic longitude/latitude-dependent absorption in the soft X-ray band. It is quite unlikely, however, that any measurement of the distribution of source distances will be made in the near future - save by analyzing statistical attributes of the gamma-ray bursts themselves. In fact, Compton's Burst and Transient Source Experiment (BATSE) may be sampling deep enough to see the effects of non- Euclidean space. The practically isotropic celestial distribution and the $V/V_{\rm max}$ distribution for gamma-ray bursts detected and localized (Meegan et al. 1992) by BATSE are most naturally interpreted in terms of either a cosmological (Mao & Paczynski 1992; Wickramasinghe et al. 1993) or heliospheric distribution of sources.

If the bursters are at cosmological distances, then the time profiles of more distant sources will be dilated relative to those of nearer sources (Paczynski 1992; Piran 1992; see also McCrea 1972). Since burst durations range over more than four orders of magnitude, with modes near 25 s and less than 1 s (Kouveliotou et al. 1993), dilation would be detectable only in a statistical sense. Most of this range in duration arises from intrinsic variations in the rest frames of the sources; only a factor of ~ 2 would be expected from cosmological expansion. A positive finding would not prove outright the cosmological hypothesis, but would increase the burden on any Galactic scenario, requiring additional ad hoc theories to explain an anticorrelation of intensity with duration. In addition, the spectral energy distribution of a burst will be redshifted - by the same factor as the temporal profile is dilated. The redshift effect should be detectable at energies below where the burst spectra begin to exhibit curvature. At higher energies, in the quasi-power-law regime, detection is problematic.

We have applied several methods to test for time dilation in bursts detected by BATSE, and report here the results of three tests which are robust in that the estimated timescales are nearly independent of the apparent brightness of the burst. The tests also address the problem of the wide distribution of temporal structure observed in bursts. We describe the preparation of burst profiles to achieve a uniform noise bias, the application and results of each test, and comparisons with simulations. We then discuss necessary refinements and the consistency of our results with a cosmological interpretation of the number-intensity relation (Wickramasinghe et al. 1993) as determined by BATSE. Our measurements, which do not yet take into account redshift effects on temporal profiles, yield a consistent picture of a relative time dilation factor of order 2 between brightest and dimmest bursts, and would thus place the more distant bursts at redshifts of order unity. The model-dependent effects of redshift will be addressed in a future paper.

2. ANALYSIS PROCEDURES AND RESULTS

We utilized burst time profiles recorded with 64 ms resolution from BATSE's Large Area Detectors (LADs). In the initial phase of the mission, burst data acquisition began about 2 s prior to burst trigger (that instant when the experiment senses that a significant rise in count rate above background has occurred) and continued to $\sim$ 240 s after (see Fishman et al. 1989, Kouveliotou et al. 1993, for descriptions of instrument and data types); since 1993 February, about 1000 s of posttrigger data have been recorded for each burst. The 64 ms data are summed over the subset of detectors which trigger on the burst. We concatenated prior to the 64 ms data four samples from a data type with lower time resolution (1.024 s), which is continuously available, summing over the same triggered detectors. (For the peak alignment test described in §2.3 we concatentated 16 such samples.) This measure includes structure that would otherwise be lost in some dim bursts which commence and rise slowly before triggering the experiment's higher time resolution modes. Each of the 1.024 s pretrigger samples was divided into sixteen 64 ms samples, with the counts randomly distributed in time and rebinned to the finer resolution. Utilization of additional 1.024 s data prior to trigger would sometimes result in loss of information in long bursts since, to minimize the effects of background curvature (see below) and to realize an interval with 2n points for the wavelet spectrum test, we truncated the concatenated time profiles at 1024 samples (65 s). Bursts shorter than 1.5 s were excluded from the analysis for two reasons. First, the BATSE sensitivity is lower for very short, dim bursts. Also, a bimodal burst duration distribution (see Mazets et al. 1981; Norris et al. 1984) is now confirmed by BATSE, and it is possible that bursts shorter than about 1 s constitute a distinct phenomenon or subpopulation (Kouveliotou et al. 1993). Out of a total sample of 590 bursts observed by BATSE, 131 were analyzed; 24 with durations shorter than 1.5 s were excluded. With the number of presently available bursts it would be difficult to determine a priori at what duration to truncate a sample of dim or bright bursts drawn from the short variety. Gaps occurring near background level were tolerated and filled with Poisson noise with the mean rate computed from intervals adjacent to the gap. The effects of dead time in our analysis are negligible for the burst sample used.

Some measure of burst luminosity must be assumed for normalization and interpretative purposes. For this we used the peak of the counting rate at 256 ms resolution summed over the four LAD energy channels (approximately: 25 - 50 keV, 50 - 100 keV, 100 - 300 keV, and $>$ 300 keV). A background interval was defined using 64 ms data from an interval (typically 96 s in duration) after cessation of the burst. The background was fitted with a first-order polynomial and subtracted from the burst rates. If the extrapolated fit did not also closely fit that portion of the pre- trigger data which was (apparently) not part of the burst, the background interval was redefined and the procedure iterated. Since bursts often contain temporal structures with heterogeneous widths and shapes, a method for estimating the peak intensity in a way that is unaffected by a rescaling of the time axis is desirable. Donoho & Johnstone (1993) describe such an algorithm: (1)

perform a wavelet transform on the time series; (2) determine a threshold (that is allowed to be different at each scale) using a risk minimization procedure; (3) delete wavelets with amplitudes that are below the threshold and diminish the others by the threshold value; and (4) reconstitute the time series by an inverse wavelet transform. At sufficiently high signal-to-noise (S/N) levels, the algorithm tends to preserve the amplitude of both broad and narrow features while significantly reducing noise fluctuations; however, intensity loss that depends on feature width is incurred if the S/N is too low. We adapted this noise reduction method for the time dilation tests, tailoring the thresholding scheme to minimize the intensity-loss problem which arises for dim bursts. We used the Haar basis (§2.2) to implement wavelet thresholding. We chose to use the data smoothed to 256 ms resolution for estimating the peak intensities because on shorter timescales preservation of structure in a manner independent of timescale is problematic for the dimmest bursts. Using simulations we demonstrated that for all bursts analyzed, the resulting peak intensity loss is 2 % or less across the observed range of structure widths. We selected bursts that fall into three brightness groups, with the extremes differing by more than two orders of magnitude in peak intensity (above background), as shown in Table 1.

In preparation for all tests the burst peak intensities, backgrounds, and noise biases were rendered uniform, with the aim of virtually eliminating brightness selection effects. After subtraction of the fitted background (Bb), the remaining "signal" profile was diminished to a canonical peak intensity (that of the dimmest burst used, 1400 counts s-1), and a canonical flat background (Bc) was added (the average background for the dimmest bursts, 5600 counts s-1). Over the fixed time interval analyzed (65 s), the actual backgrounds are relatively free of curvature and fairly constant among dimmer bursts. Backgrounds among the bright bursts vary by more than a factor of 2, but this additional variance is negligible after the signal level has been diminished. The reduced signal plus constant background (Ri) was then fractionally Poisson- distributed to compensate for reducing the original time series. The preparation procedure is thus expressed:

$$R_i = f(C_i - B_b) + B_c + V_f \tag{1}$$

where f is the signal reduction factor and Ci is the original sample value for interval i.

The required fractional variance, V_f , is obtained from

$$d_i = R_i(1-f) + f(B_c - fB_b) \tag{2}$$

$$V_f = P(d_i) - d_i, \tag{3}$$

where $P(d_i)$ is a Poisson variable (deviate) whose mean value is d_i. This procedure would result in an exact realization of a Poisson-distributed time series - with signal and background levels rendered constant - except that we must set $B_b = B_c$ to avoid negative deviates. Because the simulated Poisson noise arising from the canonical background is white, whereas the actual subtracted background sometimes contains small but nonnegligible lower frequency components, for the wavelet decomposition analysis (§2.2) small corrections of order 2 % or less were added per brightness group. The corrections were generated by comparing the wavelet decompositions of actual background noise and of simulated noise. The actual noise intervals were taken from the 64 ms data records of dim bursts which appear to have subsided soon enough to afford a flat 65 s background interval. The judgment to utilize a particular background interval for this purpose was made by fitting and subtracting a first-order polynomial and then examining the trend of residuals expressed in standard deviations.

Concomitant with time dilation is spectral energy redistribution due to redshift, which would also affect temporal measurements: Because pulses tend to be narrower at higher energy, redshifted bursts would have these narrower structures shifted to lower energies. We wish to minimize this possible effect for the present analysis. At lower energies, the disparity between pulse widths as a function of energy is not as large, and therefore redshift is less of a complicating factor. From fits to 45 isolated pulses in BATSE bursts we find the average pulse-width ratios, channels 2:1 and 3:2, to be roughly 0.85 in both cases. This is not enough of a departure from unity to mask a dilation factor of order 2; that is, temporal structure in the rest frame in the 100 - 200 keV band of bursts from distant sources redshifted to 50 - 100 keV in the observed frame would be only $\sim$ 15 % narrower than structure in bursts from nearby sources in the 50 - 100 keV band. Therefore, to perform the time dilation tests reported here, we used data summed over channels 1 and

2 (25 - 100 keV). (Pulse widths in channel 4 are often much narrower. If dim bursts are redshifted by approximately a factor of 2, narrower structure is shifted into channel 3. However, we utilized all four channels in estimating the peak intensity in order to minimize uncertainties.)

2.1 Total Normalized Counts Test

The total count, or fluence, in each prepared time profile was measured by subtracting the constant canonical background (variance arising from background is retained) and summing over the 65 s interval. Sample errors for this measure were then determined for each brightness group. Included in Table 1 are the number of bursts (N), the average total counts (S) above background summed over channels one and two, and the sample errors. All bursts are normalized to the same canonical peak intensity (flux) of 1400 counts s-1 and therefore S (fluence) can be given meaning in terms of an average "equivalent duration" - average ratio of fluence to flux. The average equivalent durations, teq, for the two dim groups, 6.6 and 6.0 s, are about twice as long as that for the bright group, 3.2 s. The difference is significant at about the 3.5 s level. Two-s fluctuations in S translate into a range in the ratio of equivalent durations of $\sim$ 1.5 - 3.

This linear average of the total counts per brightness group indicates the presence of a significant integrated effect, prompting the question: Is such a stretching of temporal features observed on each timescale present in gamma-ray bursts? Note that the same stretch factor must be observed on all timescales for the signature to be consistent with cosmological time dilation. The remaining two tests address the scaling question on timescales from 256 ms to 65 s, making more complete use of the information present in the burst profiles.

2.2. Wavelet Spectrum Test

The second test employs Haar wavelet transforms (see Daubechies 1992) to measure the amount of structure in bursts on a range of timescales. Since wavelet transforms are indexed in position and timescale, they may be superior to, for example, Fourier transforms for characterizing the spectrum of a time series which contains a variety of asynchronous, heterogeneous structures - often the case in gamma-ray bursts. The Haar wavelet is a difference operator. Among orthonormal wavelet bases, the Haar basis affords the most compact support, differencing only two adjacent intensity samples on a given scale, thereby preserving discontinuous features with the highest fidelity (however, it is not necessarily the optimum basis for characterizing the structure in gamma-ray burst profiles). A complete Haar wavelet transform is a decomposition of the profile into localized intensity differences, on a range of timescales, plus a constant component, the mean value. On timescale m and at position n, the wavelet transform of the function f(t) can be expressed (Daubechies 1992)

$$T_{m,n}(f) = a_0^{-m/2} \int dt f(t) \psi(a_0^{-m_t} - nb_0), \tag{4}$$

with constants $a_0 > 1$ and $b_0 > 0$. For our analysis y is the Haar wavelet:

$$\begin{aligned} y(t) = &\ \ 1 \qquad 0 \leq t < 1/2 \\ = &-1 \qquad 1/2 \leq t < 1 \\ = &\ \ 0 \qquad \text{otherwise.} \end{aligned} \tag{5}$$

For discretely spaced data, the time series to be differenced on each successive scale can be generated by summing pairs of intensity samples ("compressing" by a factor of 2). In this analysis the temporal range from 128 ms to 65 s is spanned in dyadic steps.

Our measure of temporal structure, or activity, on a given scale is the average of absolute values of differences between pairs of intensity values. We call this average over the position index of the wavelet transform a "wavelet amplitude spectrum." In analogy with the Fourier spectrum, phase (positional) information is lost in the summation process. Figures 1a and 1b illustrate the average wavelet spectra for the three brightness groups. The practically Poisson noise is flat, at a value of 15.1 units. We applied a small correction in computation of the noise bias, resulting in negligible differences in the curves on timescales less than 2 s (see Norris et al. 1993b). The average wavelet spectrum for the bright bursts (dashed line) lies below that for the other two groups (dotted lines) on timescales from $\sim$ 4 to 65 s. Empirical sample errors for each group are shown as envelopes (solid lines). On timescales longer than about 2 s the error envelopes are mostly determined by the ranges of durations and profile shapes within the three brightness groups. On shorter timescales noise fluctuations begin to dominate the errors; the reason for relatively smaller errors is that only a few significant short timescale features are present in a burst of average duration, whereas many more noise fluctuations are averaged to produce the 65 s wavelet spectrum. The signal on short timescales is investigated using the third test (§2.3).

To calibrate the effect seen in Figure 1 we performed simulations of gamma-ray bursts. We fitted 220 pulses in 30 bursts. The form of our pulse model is (see Norris et al. 1993a):

$$F(t) = A\ \exp(-(|t - t_{max}|/\sigma_{r,d})^{\nu}), \tag{6}$$

where t_{max} is the time of the pulse's maximum intensity, A; σ_r and σ_d are the rise ($t < t_{max}$) and decay time constants ($t > t_{max}$), respectively; and n is the pulse "peakedness" (a lower value for n results in a more peaked pulse). Combined, the parameters σ_r, σ_d, and n afford sufficient flexibility to represent virtually all pulse structure shapes in bursts. Most of the fitted pulses overlap substantially, nevertheless their sum faithfully represents the total profile on timescales longer than about 1 s (significant, shorter timescale components comprise the fit residuals in some cases). The simulations approximate distributions of several fundamental properties of burst profiles: duration, number of pulses per burst, pulse rise and decay times, and pulse peakedness. The tendency for pulses to cluster was not simulated for results discussed here. Bright bursts were simulated from the parent population of fitted pulses, preserving all fitted parameters for each burst except for the positions of pulses, which were randomized for each realization. Dim bursts were simulated in the same manner with these modifications: rise and decay times and burst durations were dilated by a constant factor. Each simulated profile with canonical background level added was Poisson distributed.

Figure 2 illustrates the results of applying the wavelet spectrum test to these simulations. The average spectra are for 100 dilated and 100 nondilated burst simulations where the relative dilation factor is 2.25. The simulated curves in Figure 2 agree fairly well with those in Figure 1, given the extents of the error envelopes. A higher curve indicates more structure, which may be manifested - under the circumstances of our intensity normalization - by a longer average duration. Essentially, the (fixed length) 65 s interval is more filled up per timescale for the dilated bursts of Figure 2 and for the dimmer bursts of Figure 1. This may seem counterintuitive; dilation might have been expected to move a given curve to the right rather than up. For simplicity, consider only processes composed of Haar wavelets of constant amplitude, independent of their timescale, τ_H, and which follow number distributions of the form

$$N_H(\tau_H) \propto \tau_H^\alpha \tag{7}$$

For processes with $\alpha < 0$, a dilation transformation with $\kappa > 1$, $N_H(\tau_H) \rightarrow N'_H(\kappa\tau_H)$, results in an increased number of wavelets on the dilated timescale by a factor $\tau_H^\alpha/(\kappa\tau)^\alpha = \kappa^{-\alpha}$. Conversely, dilation for processes with $\alpha > 0$ results in fewer wavelets on the longer timescale. In reality there must be a dependence of the number distribution on amplitude as well as timescale, and a simple power law as in equation (7) probably does not apply. For the gamma-ray burst process, dilation apparently moves *more* structure to the new (dilated) timescale, and this appears in the wavelet spectrum as an increase in summed amplitude. This demonstrates the necessity of simulating the distribution of structure in bursts with sufficiently high fidelity.

2.3. Peak Alignment Test

On timescales shorter than 2 - 4 s the wavelet spectrum test is virtually defeated by noise. To realize a test relatively free of noise bias for the shorter timescales, we introduce a refinement of the "alignment of highest peaks" technique advanced by Mitrofanov et al. (1993). After having prepared the time profiles as described in §2, we applied the same wavelet-thresholding technique used in the procedure to estimate peak intensity, thereby eliminating noise fluctuations. We then shifted the thresholded profiles in time, bringing the highest peaks of all profiles into common alignment. The peak-aligned profiles were then averaged for each brightness group. Without thresholding, the region near the average aligned peak would be contaminated by noise (since all bursts are reduced to the canonical dimmest peak intensity), and the test would be compromised. Since we are interested in preserving information near the highest peak in a symmetric manner, sixteen 1.024 s samples are concatenated prior to the burst trigger data for this test. We used burst profiles with 128 ms resolution in an attempt to observe the stretching effect on timescales as short as the S/N allowed.

Figure 3 shows the results of this test for the region within 8 s of the average peak. The structure near the peak is necessarily the most significant within a given burst, but the widths and shapes of the contributing structures in the vicinity of the average peak vary greatly. Thus, like the wavelet spectrum test, this peak alignment test examines a range of timescales. Unlike the former test, it incurs little noise bias because thresholding has eliminated the majority of insignificant fluctuations and the most significant structure has been selected by the alignment process. Using simulated sets of bursts, we estimated the intensity loss arising from thresholding to be 10 % or less for structures with full width half-maxima of 0.5 - 1.0 s (the mode for highest peaks) for the sum of channels one and two. The average profile ratio of sets with and without Poissonization and wavelet thresholding procedures provided an estimate for the intensity loss correction. These corrections were applied to the curves in Figure 3. The peak of the average profile for the bright group is significantly lower than those of the dim groups. This is not a noise effect, but must result from the bright bursts having lower peak count rates in channels 1 and 2 than do the dimmer bursts (recall that the profiles are normalized to the peak intensity of all four channels summed). Spectral energy redistribution arising from redshift may be the explanation for this effect. There is a clear trend on timescales $\tau_w > 0.5$ s: across five octaves in width the average profile for the bright bursts is approximately one-half as wide as the average profiles for the dim and dimmest bursts. If we normalize the peak of the average profile for the bright bursts to unity, the differences in width of the average profiles are still significant for $\tau_w > 0.5$ s. If the deficit for bright bursts is due to spectral redshift, then a self-consistent treatment would also require propagation of the narrower temporal structures in higher energy bands to lower energy bands, as discussed in §2.

We estimated the uncertainties of the peak alignment test by performing one 100 sets of simulations in the manner described above, each set consisting of 50 dilated and 50 nondilated profiles, again with a constant dilation factor of 2.25. Figure 4 illustrates the application of the peak alignment test to these simulations. The envelopes (solid lines) contain 68% of the profiles per group. From visual inspection, we conclude that the differences in the average profiles of dim and bright bursts in Figure 3 are significant at about the 2 to 4 s level per octave in width (although, each octave in width does not represent an independent quantity as in the wavelet spectrum test). As noted previously, our simulations do not reproduce all of the narrow structure observed in actual bursts, hence in Figure 4 the profile uncertainties within ~ 0.5 s of the average peak are not well modeled.

3. DISCUSSION

We selected bright and dim gamma-ray bursts detected by BATSE according to their peak intensities. We performed a procedure to render uniform the burst signals, backgrounds, and noise biases, thus virtually eliminating any brightness selection effects. An ensemble measure of the fluence to flux ratio is twice as large for dim bursts as for bright ones, suggesting that to first order, the dimmer bursts have durations which are twice as long. Combined, a wavelet spectrum test and a peak alignment test calibrated with burst simulations confirm that a "stretch" ratio of ~ 2 is manifest over seven octaves in width of temporal structure, from 0.5 to 65 s. The efficacy of the latter two tests is that they segregate (wavelet spectrum) or order (peak alignment) the information in a time profile by width of temporal structure, and thus tend to address the dispersion which arises from the wide variety of time profiles. The capability to resolve profiles into components actually takes advantage of the intrinsic dispersion: the stretching effect must be present on all timescales to be consistent with cosmological time dilation. The peak alignment test affords a stretch measure on shorter timescales than does the wavelet spectrum, essentially because the most significant narrow features of bursts are selected and averaged. Wide (> 8 s), low-intensity structures are not as well estimated by the peak alignment test because our noise thresholder has been optimized for intense features. The wavelet spectrum test is more accurate for measurements on long timescales since broader burst structures, containing more counts, dominate over noise.

We note that Mitrofanov et al. (1993) designed a similar peak alignment procedure to search for effects like time dilation and found a negative result when applied to bursts detected by the APEX experiment on PHOBOS 2. We believe there is not necessarily an inconsistency with our result since their dynamic range in peak intensity was approximately an order of magnitude less than BATSE's, suggesting that APEX did not sample sufficiently distant sources to observe the effect. Lestrade et al. (1992) found a positive effect in a subsample of short bursts detected by PHEBUS (again with a much smaller dynamic range in peak intensity than BATSE's), but given the clear bimodality in the burst duration distribution with a minimum near 1.5 s (Kouveliotou et al. 1993) - equivalent to the duration cutoff of their sample, it is difficult to interpret their result.

Some effects which we do not yet take into account would tend to increase the observed differential signal. As explained in §2, redshift of the energy spectrum is a competing effect since at higher energy, pulses tend to be narrower. A temporal analysis taking into account such a "K- correction" is somewhat more complex, and dependent upon an assumed cosmology. From energy-dependent pulse-shape fits, we estimate correction for redshift would tend to increase the apparent time dilation effect by 10 % - 20 %. However, spectral redistribution arising from redshift would tend to decrease the effect by a comparable amount. A precise background model would allow the use of time series longer than 65 s, and the analysis of the complete event in practically all cases. This would tend to include preferentially more structure for dim bursts since they are, on average, longer. Also, since we have fitted backgrounds (apparently) after burst cessation and since bursts tend to be asymmetric on all timescales (Nemiroff et al. 1993a), such that burst "envelopes" decay more slowly than they rise, for dim bursts our background subtraction will tend to remove some signal if the event decays slowly enough. Better background estimation will alter our results only on the longest timescales. We will address these problems in a future paper.

Finally, the effects of an intrinsic luminosity distribution must be modeled if more precise comparisons are to be had with interpretations (Fenimore et al. 1993; Wickramasinghe et al. 1993) of burst number-intensity relations determined by BATSE and other instruments. However, we can make a coarse comparison of our result with such analyses at this stage. For the first 260 bursts detected by BATSE, the average values of Cmax/Cmin for the bright, dim, and dimmest groups are 34.5, 2.10, and 1.75, respectively. The C-max/Cmin parameter is about a factor of 2 larger than the Cpeak/Ccom measure used in Wickramasinghe et al. (1993). From this we see that our dimmest group is near the 99% completeness limit for BATSE ($C_{\rm peak}/C_{\rm com} = 1$), which, as determined from Figure 2 of

Wickramasinghe et al., corresponds almost exactly with a redshift of one. Therefore, we consider our result, $z \sim 1$, to be in good agreement with independent fits to the BATSE number-intensity relation.

Given the state of knowledge of burst mechanisms, the anticorrelation of brightness with duration admits alternative explanations. For example, if the mechanism is such that total energy per burst is approximately constant, then release of energy at a slower rate, corresponding to a lower luminosity, would result in longer bursts. However, this exact proportionality is not what we observe. Also, if the bursters are cosmological, it is entirely possible that evolutionary effects complicate the picture; for example, the duration and peak intensity distributions could evolve with time.

Table 1

Total Normalized Counts Test

Brightness Group	Peak Intensity[a] cts s^{-1}		N (bursts)	τ_{eq} (s)	Σ^b	$+1\ \sigma$	$-1\ \sigma$
	Min	Max					
Bright	18,000	250,000	41	3.2	4490	1050	420
Dim	2,400	4,500	44	6.0	8340	1030	1400
Dimmest	1,400	2,400	46	6.6	9300	1870	1240

[a] Peak intensity summed over LAD channels 1 - 4.

[b] Average total counts summed over channels 1 and 2.

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FIGURE CAPTIONS

Figure 1: Average wavelet amplitude spectra of BATSE bursts for three brightness groups, described in Table 1: (a) dim and bright, (b) dimmest and bright groups (dotted and dashed respectively). Solid lines indicate empirical plus/minus 1 s envelopes for respective samples. Longest timescale (2^7 x 512 ms) is 65 s.

Figure 2: Similar to Fig. 1, for simulated dilated (dotted) bursts and nondilated (long dash) bursts. Dilation factor = 2.25, 100 bursts per group.

Figure 3: Average wavelet-thresholded profiles of BATSE bursts in three brightness groups, with highest peak for each burst shifted into temporal alignment. Dimmest (solid, outer profile), dim (dotted), and bright groups (solid, inner profile).

Figure 4: Similar to Fig. 3. Average aligned, wavelet-thresholded profiles for 100 simulation sets each of dilated (dotted) and nondilated (long dash) bursts, 50 bursts per set. Dilation factor = 2.25. Envelopes (solid lines) contain 68% of the profiles per group.