DURATION DISTRIBUTIONS OF BRIGHT AND DIM BATSE GAMMA-RAY BURSTS

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ABSTRACT

We have measured the T90 and T50 durations of bright and dim gamma-ray bursts (GRBs) detected by the Compton Gamma Ray Observatory's Burst and Transient Source Experiment (BATSE). The T90 (T50) duration is defined as the interval over which 5% (25%) to 95% (75%) of the burst counts accumulate. Out of 775 bursts observed by BATSE, 159 bursts were analyzed; bursts with durations shorter than 1.5 s were excluded. A Kolmogorov-Smirnov test yields a probability of 6 x 10^{-5} that the T50 durations of the dim and bright samples are drawn from the same parent population. We find that the centroid and extent of the duration distribution for the dim sample are scaled by approximately a factor of two relative to those of the bright sample. The measured time dilation factor is not sensitive to choice of energy band. These results are quantitatively consistent with previous tests for time dilation in a smaller sample of BATSE bursts. The dimmer bursts, if cosmological, would lie at redshifts of order two.

Subject headings: cosmology: theory - gamma rays: bursts

1. INTRODUCTION

Over one thousand gamma-ray bursts (GRBs) have been detected by the Burst and Transient Source Experiment (BATSE) on the Compton Observatory. Analysis of refined positions for three-fourths of the bursts still indicates no significant deviation from isotropy, whereas their number-intensity relation implies an effective limit to the depth of the spatial distribution (Meegan et al. 1994). Norris et al. (1994a) and Davis et al. (1994) performed several tests, and found a time dilation factor of approximately two between bright and dim bursts. Using the same brightness groupings (see Table 1), Nemiroff et al. (1994) report a significant difference in spectral hardness ratios as a function of time, possibly consistent with cosmological redshifts. These findings, consistent with predictions by Paczynski (1992) and Piran (1992), lend increasing support to the cosmological hypothesis, especially in light of interpretations of the number- intensity relation which are consistent with redshifts of order 1 - 2 for the dimmer bursts (Mao & Paczynski 1992; Wickramasinghe et al. 1993; Fenimore et al. 1993). (Also, in the general context of cosmological time dilation, see Noerdlinger [1966] and McCrea [1972].) However, analysis of a different sample of BATSE bursts (Mitrofanov et al. 1994), more uniformly spread in intensity and not representing the dim and bright samples of Norris et al. (1994a) did not find a significant time dilation effect.

In this paper we adopt an objective definition of the "duration" of a burst, and then study the dependence of this quantity on brightness, using the same peak intensity groupings as in Norris et al. (1994a). We introduce modifications to the procedure used by Kouveliotou et al. (1993) to obtain T90 and T50 duration estimates. The modifications realize an automated procedure for estimating burst durations, while using a noise reduction technique to reduce variances which arise from finite counting statistics and heterogeneous burst profiles. Brightness selection effects are avoided by rescaling all bursts to fiducial levels of peak intensity and noise bias; the analysis is also performed without such equalization of the signal-to-noise (S/N) level. We find that the centroid and extent of the duration distribution for the dim sample are scaled by approximately a factor of two relative to those of the bright sample, in good agreement with the time dilation factor found from multi-resolution tests (Norris et al. 1994a), and consistent with cosmic time dilation.

2. ESTIMATION OF DURATIONS

We analyzed burst samples in three peak intensity ranges (described in Table 1), using data from BATSE's Large Area Detectors (LADs). The burst duration distribution is bimodal, the modes of the sample in the BATSE first catalog being 330 ms and 25 s, as shown by Kouveliotou et al. (1993). To avoid any possible trigger selection bias, we elected to study only the long mode of the duration distribution and therefore excluded bursts shorter than $\sim$ 1.5 s. Thus, of a total sample of 775 bursts detected by BATSE, 159 were analyzed - those bursts longer than 1.5 s and within the intensity ranges in Table 1. Following Kouveliotou et al., we utilized count rates summed over the four LAD channels ($>$ 25 keV); we also performed the analysis for channels 2 - 3 (58 - 320 keV) and for channel 3 (115 - 320 keV). Peak intensities were determined on a 256 ms timescale, following a procedure similar to that described in Norris et al. (1994a), with one salient difference that allowed examination of time intervals of at least 340 s: we utilized 100 s of pretrigger data with 1.024 s resolution in addition to the high resolution (64 ms) data contained in the burst record. Each of the 1.024 s pretrigger samples was divided into sixteen 64 ms samples, with the counts randomly distributed in time at the finer resolution (thus preserving Poisson statistics); the pretrigger and burst record data were then concatenated in correct temporal registration. The concatenated time profiles were binned to 512 ms for further analysis.

Visual examination of the time profiles in the three lowest LAD energy channels (25 - 50 keV, 50 - 100 keV, 100 - 300 keV) yielded coarse estimates of burst durations. Pulse structures are often more easily discernible at higher energy, whereas burst envelopes persist longer at lower energy. For bursts with apparent total durations shorter than 131 s (2048 samples times 64 ms; $2n$ points required for analysis procedure), backgrounds were fitted using a quadratic form. Adequate background fits necessitated fourth or fifth order polynomials for twelve longer bursts (4096 samples used). In order to eliminate brightness selection effects on the duration measures, we diminished the background-subtracted profiles to a canonical peak intensity, added a canonical constant background, and equalized the Poisson counting rate. The canonical peak intensity chosen (1400 counts s^{-1} was that of the dimmest burst used in the study. This equalization procedure is detailed in Norris et al. (1994a). However, because there is a tradeoff between addressing brightness selection effects and preserving original signal-to-noise levels, the entire analysis was also performed without equalization of the S/N level.

Kouveliotou et al. (1993) measure the T90 duration, defined to be the interval between times when 5% and 95% of the burst counts (above background) are accumulated. Similarly, T50 is the interval between 25% and 75% of the cumulative counts. We also generate these measures, but using an automated procedure, once backgrounds are fitted and subtracted. Two features of our approach combine to reduce the effects of statistical fluctuations. First, each profile is passed through high and low pass filter networks (Donoho 1993; Donoho & Johnstone 1994). The high pass filter network is a Haar wavelet transform in dyadic steps (Daubechies 1992), followed by application of a (possibly different) threshold at each timescale represented in the wavelet transform, and then an inverse wavelet transform (see Norris et al. 1994a). Thresholding on each timescale for the high pass filter results essentially in removal of wavelet coefficients which represent less than one sigma differences from point to point. The low pass network is the sequence of compressed time profiles, also in dyadic steps. The low pass filter also removes wavelets of the same amplitude range, but measured against the ambient background level rather than against the ensemble of wavelet amplitudes. The efficacy of such high and low pass filters is that statistical fluctuations about background level are largely deleted, while significant burst structure is preserved. Using simulations, we have demonstrated that this multi-resolution approach preserves temporal shape (on timescales $>$ 128 ms) to relatively high precision.

Second, the same low pass filter procedure was used as a "floating trigger" (much as the BATSE experiment itself has triggers on three timescales), to determine lower and upper limits on the t_0 (onset) and t_{100} (cessation) times of the burst, respectively. These limits for the t_0 and t_{100} points were determined within the 131 s intervals for bursts with quadratic background fits, and within the 262 s intervals for the twelve longer bursts. The initial t_0 and t_{100} points were assigned the times of the last and first bins, respectively, of the burst profile. Successively for each timescale, the t_0 (t_{100}) point was decreased (increased) to the time of the earliest (latest) fluctuation of at least one sigma significance above background. The threshold was reduced by the factor 1/2 for each dyadic compression of the time series, thereby maintaining a constant threshold level across all timescales. Thus, long structures of lower intensity tend to be included as part of the burst by this multi-resolution technique while shorter structures of higher (but insignificant) intensity are ignored. The floating trigger was operated on timescales from 512 ms to 32 s. To compensate for discretization, the interval thus found was lengthened at start and end by 16 s (half the longest timescale) to yield the nominal t_0 and t_{100} points. Each time profile was then integrated between these times to compute the t_5,t_{95} and t_{25}, t_{75} points. Note that the first step, thresholding of the wavelet coefficients, considerably reduces the random walk between the nominal t_0 and t_{100} points and the actual burst onset and cessation times, respectively.

Two important consistency checks were then performed. Figure 1 compares the T90 and T50 duration determinations for the bright bursts with original signal-to-noise levels and without application of the high and low pass filter procedure (dotted line) to the determinations with noise biases rendered equal to that of the dimmest burst analyzed and with the filter applied (solid line). For the noisy profiles, durations were determined from the median of eleven realizations of the S/N equalization procedure (in the large majority of cases, the median was representative of most of the eleven measurements). The small differences between the two T90 distributions (Figure 1a) are consistent with statistical fluctuations. More to the point, the centroids and widths of the two are practically identical. As T50 measures the core of the burst, where the intensity levels tend to be well above background, one expects this measure to be less sensitive to the S/N equalization procedure. Further, T50 should be less affected by outlying structures. Thus, regardless of the particular measurement procedure employed, T50 estimates may be more reliable - in the sense that brightness selection effects are less pronounced. In fact, the T50 distributions (Figure 1b) for the two approaches are in slightly better agreement than the T90 distributions. We also compared our T90's with those published in the first BATSE catalog (Fishman et al. 1994). For the eighteen bright bursts which appear in the catalog, fourteen had comparable determinations. Durations for four bright bursts with outlying, low-intensity structures of very low-significance were underestimated by our technique. We note that statistical fluctuations in intrinsically dim bursts would often obliterate such features - thus the rationale for performing the S/N equalization procedure. In fact, our determinations for dim bursts are in closer agreement with those in the first BATSE catalog than our determinations for bright bursts.

The estimated T90 and T50 duration distributions for the three intensity samples are illustrated in Figures 2 and 3, with (Method 1) and without (Method 2) application of the S/N equalization procedure, respectively. Below, results from Method 1 are listed with those from Method 2 following in parentheses. For both methods, there is a clear shift of the two dim samples to longer timescales with respect to the bright sample. To estimate if the duration distributions could have been drawn from the same parent distribution, we performed a two-distribution Kolmogorov- Smirnov (KS) probability analysis (Press et al. 1992). The T90 durations for the bright group were multiplied by a time dilation factor. The artificially dilated durations were then statistically compared with the those of the dim samples combined. This was done for candidate time dilation factors ranging from 1.0 to 4.0. The results are shown in Figures 4a & 4b for Methods 1 and 2, respectively. The duration distribution for the brights is most similar to that of the dims when a time dilation factor of 1.9 (2.1) is applied - and the KS statistic indicates that the goodness of fit is acceptable for both methods. A time dilation factor of unity would yield a KS statistic lower than that observed only once every 1500 (1500) trials. The horizontal line depicts the level above which there is at least a 31.6% chance that the brights and dims were drawn from the same parent population. Method 2 produces distributions of more comparable logarithmic width (discussed below) than does Method 1. This is reflected in the fact that the maximum KS statistic, corresponding to the best time dilation factor, is nearer unity for Method 2. Figures 4a & 4b also show the KS statistic for the T50 duration distributions. The best fit time dilation factors were found to be 2.2 (2.4). For the T50 measure a time dilation factor of unity would yield a lower KS statistic than that found only once in 16,000 (26,000) trials.

To estimate centroids and widths, we fitted a Gaussian form to the T90 and T50 distributions, binned logarithmically with 5 bins per decade (fits with 10 bins per decade yielded practically identical results). The results are listed in Table 1 for the three brightness samples and for the two dim groups combined. A Gaussian form affords an adequate, but not optimal, estimate of the moments of the duration distributions. Whereas the KS test tends to emphasize the central region of a distribution, a Gaussian fit takes into account shape contributions from the wings. Again, a clear shift of approximately a factor of two is manifest between the centroids of the bright and combined dim sample distributions. For the T90 measure the ratio of the centroids is 2.1 (2.4); for T50, the ratio is 2.2 (2.3). For both measures, considering the two dim samples separately yields somewhat discrepant results: via Method 1, T90 and T50 centroids for the dimmest group are lower (33.4 s and 11.8 s, respectively) than for the dim group (43.6 s and 15.4 s, respectively). Some possible explanations for these disparate values are discussed in the next section.

To search for any trend in time-dilation factor with energy, we also performed the analysis for channels 2 - 3 (58 - 320 keV) and for channel 3 (115 - 320 keV). Fewer counts are available as fewer channels are included, but an improvement in signal-to-noise level is realized by excluding channel 4, in which the count rate is relatively low (emission is often indiscernible in channel 4 for dim bursts). Centroid and logarithmic width determinations were comparable in all three energy ranges. Table 2 summarizes the ratios of centroids (time-dilation factors) - bright sample compared with combined dim and dimmest samples - for the several combinations of energy band, method, and duration definition. There is no apparent trend with increasing energy. The errors in time-dilation factor, of order 0.25 unit, are comparable to the variations between methods and between T90 and T50 measures.

Inspection of Figure 2 and Table 1 reveals that for Method 1, the bright burst distribution is significantly narrower than any measure of the width of the distribution of dim bursts. Logarithmic widths (Gaussian standard deviation in logarithm of time) for the latter groups range from 0.41 $\pm$0.03 (in log [seconds]) to 0.54 $\pm$ 0.04, whereas for the bright sample the values are 0.34 (0.35) $\pm$ 0.03 for T90 (T50). For Method 2 the difference in logarithmic widths is still present, but less significant (see Figure 3) except when comparing the T50 measures for the bright and dimmest samples. Note that for pure time dilation, neglecting all other effects, the distributions should have the same widths in logarithm of time. Assume for sake of argument that Method 1 gives better estimations:

It would appear that the sample cutoff of 1.5 s cannot wholly account for the narrower bright distribution since for the T90 measure, no durations are determined to be less than 5 s. It is possible that the measured disparity in distribution width arises from finite sample size. We find from redistributing the durations of only five bright bursts in the two highest bins (10 - 25 s; see Figure 2) into the two adjacent bins, that the logarithmic width broadens to 0.40. Also, for the optimum time-dilation factors of 1.9 and 2.2, the KS test for Method 1 (see Figure 4) yields probabilities of 0.56 (T90) and 0.63 (T50), respectively, that dim bursts and time-dilated bright bursts are drawn from the same parent population. For Method 2, the corresponding maximum probabilities are probabilities of 0.97 (T90) and 0.67 (T50). We conclude that, within measurement errors, the logarithmic widths of the bright and dim distributions are consistent with pure time dilation. Note, however, that other physical processes intrinsic to the burst source may give rise to significant effects which modify the relative shapes of the duration distributions. In the next section we briefly explore this possibility.

3. DISCUSSION

We have estimated centroids and logarithmic widths of duration distributions of bright and dim BATSE gamma-ray bursts. The determinations are in good agreement with previous multi- resolution tests which, when calibrated with simulations, yielded an average time-dilation of 2.25 between bright and dim groups (Norris et al. 1994a). This is in good agreement with the time- dilation factor found for the T90 and T50 duration measures, whether one considers the method utilizing original signal-to-noise levels or the method of equalizing noise biases to yield more reliable results. With current sample sizes, Kolmogorov-Smirnov tests allow the rejection of the hypothesis that the samples are drawn from the same parent population at a confidence level of 6 x 10^{-5}. Thus, the appearance that previous experiments (Mazets 1981; Norris et al. 1984; Klebesadel 1990; Hurley 1991) preferentially detected bursts shorter than BATSE bursts (in the duration range above 1.5 s) could be explained by the fact that those experiments had less sensitivity and therefore sampled the bright end of the number-intensity relation. We suggest that attempts be made to apply rigorously equivalent methods for duration measurement and to intercalibrate instruments, and thereby increase the number of bright bursts which may be compared with BATSE-detected dim bursts.

Recall that for both the T90 and T50 measures the distribution centroids of the dimmest group are lower than for the dim group. We discuss several possible explanations. Two possible systematic trends that might have been introduced by the analysis method - which we believe to have negligible effect on the overall shapes of the distributions - are background subtraction and truncation of the analyzed "burst interval" at 131 s or 262 s. For progressively dimmer events, onset and cessation of emission becomes more difficult to apprehend. Thus in some dim bursts, we may have selected background regions where in fact some very low level emission occurs. Also, one dim burst in our sample is known to have a T90 duration of $\sim$ 430 s - the additional emission comes prior to the 100 s of pretrigger data which we utilize. There are probably a few additional dim bursts in which we have missed such precursor emission, but this cannot have affected the bulk of durations for the dimmest group. A third explanation of the disparity in centroids for the dim and dimmest groups requires the assumption of cosmological origin: the dimmer bursts are more redshifted, and therefore narrower structure from higher energy is shifted into the BATSE LAD energy range, effectively shortening each pulse structure (but, see below). Evaluation of this possibility will require detailed comparison of observations and models. Finally, the difference may be purely attributable to sample variations.

If bursters are at cosmological distances, a duration measure such as T90 or T50 may well prove to be as good or better a time dilation indicator as multi-resolution measures of burst structure: duration estimation for entire bursts, which average $\sim$ 10 pulses (Norris et al. 1994b), should be less subject to energy-dependent pulse width narrowing which would arise from spectral energy redshift. Indeed, by performing our analysis for different energy bands, we have shown that there is no apparent trend of duration time-dilation factor with energy. We note however that, by itself, duration does not address the necessary condition that all structures and intervals between structures be time dilated by the same factor. New tests which measure pulse widths and intervals between pulses do corroborate previous multi-resolution tests for time dilation (Davis 1994).

Assuming the bursters are at cosmological distances and following the treatment of Wickramasinghe et al. (1993), we determine that the median peak intensity (39,000 counts s^{-1}) of the bright sample would fall at a redshift, z, of $\sim$ 0.3. As discussed in Norris et al. (1994a), "K- corrections" for energy-dependent pulse width and spectral redistribution arising from redshift must be applied, and modeling of intrinsic luminosity functions performed to arrive at quantitative comparisons with theory. But if we take the duration dilation factor found in this study to be relatively free of the spectral complications that must be considered for shorter structures, then from $(1 + z_{dim})/(1 + z_{bright}) \sim 2.25$, we can estimate for our dim sample that $z_{dim} \sim 2$. This is considerably higher than the redshift (≈ 0.8) found for dim BATSE bursts by combining the PVO and BATSE number-intensity relations, assuming no source evolution with cosmic time (Fenimore et al. 1993). Emslie & Horack (1994) have shown that only narrow (redshift-independent) luminosity functions can be accommodated by the BATSE number-intensity relation unless a finite cosmological constant is invoked and that z $\sim$ 1.25 would be indicated for the dimmest BATSE bursts. However, the acceptable parameter space for the cosmological hypothesis is much wider if bursters evolve with cosmic time either in luminosity or rate of occurrence, or both. For example, if $z_{dim} \sim 2$, then pure rate evolution with a redshift dependence of $(1 + z)^{0.6}$ provides an acceptable fit to the BATSE number-intensity relation (Horack, Emslie & Hartmann 1994).

Recently, Brainerd (1994) and Yi & Mao (1994) have discussed the complicating special relativistic (SR) effect of beaming, which is necessary in many cosmological (or even Galactic halo) scenarios to account for production and/or survival of high-energy gamma-rays (Dingus et al. 1994). Brainerd showed that a spatially limited distribution of sources in Euclidean space can exhibit an inverse correlation of intensity with duration, and that beaming is one mechanism which would operate in that context to produce such an average correlation. However, Wijers & Paczynski (1994) show generally that for local (noncosmological) source populations with distance-independent luminosity functions, the duration distributions for high and low intensity burst samples will have different cutoffs at short durations, but both distributions will extend to the same cutoff at long durations. This is in contradistinction to our result, in which the distributions appear to exhibit a relative shift. Wijers & Paczynski, using burst durations from the first BATSE catalog (Fishman et al. 1994), find a result similar to ours, supporting a shift in distributions rather than just a difference in the short duration regime. Again, a shift with distribution shape preserved in logarithm of duration is the expectation for pure cosmological time dilation. Since detailed models of duration distributions resulting from assumption of various luminosity functions and spatial distributions is yet to be presented, it is judicious to reserve judgment on the meaning of our results.

An important study, assuming trigger selection effects can be correctly understood, will be analysis of bright and dim bursts with durations < 1.5 s. Short bursts share the same peak intensity range as long bursts (Kouveliotou et al. 1993), and may in fact be the same population (Norris et al. 1994b). Since pulses in short bursts are narrower than those in long bursts, and since cosmological time dilation requires all intervals to be stretched equally, additional constraints on beaming and cosmological hypotheses should come from considering both short and long bursts.

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FIGURE CAPTIONS

Fig. 1. - Duration distributions for bright BATSE bursts. T90 (a) and T50 (b) durations are measured from 5% to 95%, and 25% to 75%, respectively, of integrated counts above fitted background in the energy range > 25 keV. Solid line: with S/N levels rendered equal (to that of the dimmest burst analyzed) and with high and low pass filters applied. Dashed line: with original signal-to-noise levels and without application of the filter procedure.

Fig. 2. - T90 (a) and T50 (b) duration distributions for bright (solid), dim (dashed), and dimmest (dotted) BATSE burst samples. S/N levels are rendered uniform (Method 1, see text). Median duration from 11 noise realizations per burst is plotted. Bursts with apparent total durations less than 1.5 s are not included.

Fig. 3. - Same as Figure 2, but duration analysis performed with original S/N levels preserved (Method 2).

Fig. 4. - (a) Unbinned Kolmogorov-Smirnov test between bright and dim duration distributions for Method 1. Durations of bright bursts were multiplied by candidate time-dilation factors and compared to the durations of the two dim samples combined. The solid and dot-dashed lines illustrate probability as function of dilation factor for T90 and T50 durations, respectively, that dim and time-dilated bright durations were drawn from the same parent distribution. Best time-dilation factors are 1.9 (T90) and 2.2 (T50). (b) Same as (a) but for Method 2. Because the distribution widths measured with Method 2 are more nearly equal, the best time-dilation factors (2.1 for T90 and 2.4 for T50) result in higher probabilities that the dim and bright samples are drawn from the same population.