GROSS SPECTRAL DIFFERENCES BETWEEN BRIGHT AND DIM GAMMA-RAY BURSTS

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

[1] *NASA Goddard Space Flight Center, Greenbelt, MD 20771*
[2] *George Mason University, CSI Institute, Fairfax, VA 22030*
[3] *Universities Space Research Association*
[4] *Dept. Astronomy, University of Pennsylvania, Philadelphia, PA 19104*
[5] *NASA Marshall Space Flight Center, Huntsville, AL 35812*
[6] *University of Alabama, Huntsville, AL 35899*

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ABSTRACT

We find that dim gamma-ray bursts (GRBs) are softer than bright GRBs, as indicated on average by data from the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory. We show that this correlation is statistically significant with respect to variations due to random differences between GRBs. This effect is discernable using a variety of methods and data sets, including public domain data. We analyze several types of systematic errors and selection effects in the BATSE data and conclude that the observed effect is not dominated by any of them. We therefore assert that this dim/soft effect is a real property of GRBs. It is possible that this correlation is a consequence of the time dilation detected by Norris et al. (1994) and that the burst sources are located at cosmological distances.

Subject headings: cosmology: theory - gamma rays: bursts

1. INTRODUCTION

The Burst and Transient Source Experiment (BATSE) on board NASA's orbiting *Compton* Gamma Ray Observatory has yielded more data on gamma-ray bursts (GRBs) than any other instrument. The observed isotropic distribution of bursts (Meegan et al. 1992) combined with a relative paucity of dim bursts (Fishman et al. 1992) have failed to bolster the generally accepted Galactic origin of GRBs that had emerged from analysis of data of brighter bursts from satellites in the 1980s (Atteia et al. 1987). Today, the origin of GRBs still remains an enigma, with more than 100 models published in the refereed literature (Nemiroff 1994). Paczynski (1992) and Piran (1992) interpreted early BATSE data as consistent with a cosmological origin of GRBs and predicted that more distant bursts would show both a time dilation and a spectral shift relative to closer bursts. The isotropic distribution of bursts detected by earlier spacecraft also prompted expectations of cosmological effects (Usov & Chibisov 1975, van den Berg 1983). Recently, Norris et al. (1994) and Davis et al. (1994) have reported measurements of a relative time dilation of order two between bright and dim GRBs.

Previous claims of spectral differences between bright and dim GRBs were reported by Mitrofanov et al. (1992a, 1992b, 1993) who analyzed data from 62 GRBs from the Soviet-French experiment APEX on board the *Phobos 2* spacecraft. Paciesas et al. (1992) found a similar effect with analysis of the first 126 GRBs detected by BATSE. Here we present new evidence that dim GRBs, selected from the first 750 GRBs recorded by BATSE, do indeed show gross spectral differences compared to bright GRBs. This effect was initially apparent but only briefly described in Norris et al. (1994), appearing as a difference in average peak intensities. In this paper we quantify the significance of the effect in several ways, including as a function of time. Mitrofanov et al. (1994) also report the same effect in a smaller sample, but characterize the uncertainties in terms of statistical errors only - they did not evaluate hardness variations in different peak intensity samples. The correlation of spectral hardness and peak intensity is distinct from the evidence reported by Dezalay et al. (1992) and Kouveliotou et al. (1993) that short (< 2 s) duration GRBs tend to be spectrally harder than long (> 2 s) GRBs. Spectral properties of bright BATSE detected GRBs are also discussed by Schaefer et al. (1992, 1994) and Band et al. (1993).

In §2 we present our evidence for gross spectral differences, comparing bursts in the same peak intensity ranges in which relative time dilation was found by Norris et al. (1994). In §3 we present evidence that such an effect is discernable, although less statistically significant, in 482 bursts contained in the second BATSE catalog with recorded fluences. In §4 we discuss possible systematic errors and in §5 we discuss the results.

2. PRIMARY DATA AND RESULTS

We inspected all GRB data recorded by BATSE before 15 September 1993 and created two distinct subsets of GRBs based on their wavelet smoothed 256-ms peak count rate P - a "bright" subset of GRBS with $18,000 < P < 250,000$ and a "dim" subset with $1400 < P < 4500$, where P is measured in counts $\sec^{-1}$ in all triggered BATSE Large Area Detectors (LADs) in all energy channels combined. Only GRBs with durations greater than 1.5 seconds were included, for reasons discussed in Norris et al. (1994). There were 45 GRBs in the bright subset, which comprises ~ 6 % of the GRBs measured by BATSE at the time, and 114 in the dim subset, which is near the flux where BATSE is 99 % complete in detecting GRbs. From the work of Wickramasinghe et al. (1993) and consideration of peak fluxes for bursts near the low end of the peak intensity range of our bright sample, we find that the brights are potentially at a significantly smaller redshift than the dim bursts, assuming that GRBs are cosmological.

We define a hardness ratio, $H(t)$, designed to be relatively insusceptible to coordinate singularities (such as zero appearing in the denominator) and at the same time not biased toward bright events:

$$H(t) = \frac{\sum_k 2\ C_3^k(t)/(C_2^k(t) + C_3^k(t))}{\sum_k 2\ C_2^k(t)/(C_2^k(t) + C_3^k(t))}. \qquad (1)$$

Here t designates time relative to the time of peak intensity, $C_i^k(t)$ stands for counts of GRB $\#k$ above background in energy channel i, where channels 2 and 3 are approximately 50 - 100 keV and 100 - 300 keV, respectively. When either $C_2^k(t)$ or $C_3^k(t)$ is less than two sigma above the respective background for that channel for any k, the contribution of that burst k was excluded from the sum in equation (1).

We utilized approximately 100 seconds of 1.024-s resolution data, prior to burst trigger time, concatenated with at least 230 s of 64-ms resolution data in order to fit a quadratic form to the background. Similar results were obtained with a first order polynomial background fit, but a quadratic affords a flat burst region over at least 128-s in the vast majority of cases.

For each subset of GRBs we aligned the highest peak, determined on a 1.024-s time scale, and cumulatively added H for each time bin relative to this highest peak. Figure 1 depicts the difference in average hardness profiles between the two burst groups. For the bright burst sample, the uncertainties are determined primarily by the differences among hardness ratios of GRBs, rather than by inaccuracy in the determinations for individual GRBs. For dim bursts, statistical fluctuations play a larger but still minority role in the overall error budget. The error bars shown therefore depict one sigma sample errors: 68% inclusion of individual determinations, reduced by $\sqrt{N-1}$, where N is the sample size.

The sense of the spectral difference we have found is that the dim bursts are on average softer than the bright bursts, in the interval within 8-s of the peak of the average profiles. We have found this spectral difference in several different ways using different subsets of the BATSE data. From the error bars depicted in Figure 1, we see that the hardness ratios of the bright and dim groups differ at about the 3 sigma level near the central time bin, and at about the one sigma level for many of the other time bins tested.

3. EFFECT EVIDENT IN SECOND BATSE CATALOG

As of this writing 482 BATSE detected GRBs have entered the public domain which have recorded fluences and peak fluxes (Meegan et al. 1994). To search for gross spectral differences in the public domain data, we used the fluences for channels 1, 2, 3 and 4 (referred to as F_1 through F_4 respectively) as well as the peak flux on the 64 millisecond scale integrated over all 4 channels (P_{64}) to perform the described test.

We first divided the data into a bright half and dim half as determined by P_{64}. Then, to test for a brightness - hardness correlation, we defined the same type of cumulative hardness sum used in equation (1) ($H_{i/j}$ between energy bands i and j, except this time using the whole fluence of bursts instead of flux at given relative times) for both samples and compared them statistically. We searched for a brightness - hardness correlation using channels 4 and 3, channels 3 and 2, and channels 2 and 1 for each sample. One σ errors were determined as above from the sample variance.

Values for these hardness ratios are shown in Table 1. Column 1 of this table gives the energy channels being used. For example, a "3/2" in column 1 denotes a row where the hardness ratio of the fluence in channel 3 divided by the fluence in channel 2 is given. Column 2 lists the hardness statistic for the first 2 years of BATSE data in the public domain with P_{64} below the median value. Column 3 lists the same hardness statistic for these GRBs in the public domain with P_{64} above the median value. Column 4 lists the significance of the difference between the column 2 and 3 values as determined from the combined variances of both samples. This significance implicitly assumes a Gaussian form for the variance.

From inspection of Table 1 we see that the high P_{64} half of the public domain bursts are significantly harder than the dimmer half. High statistical significance, above the 4 σ level, is seen both when computing the cumulative hardness ratios between channels 3 and 2, and between channels 2 and 1. The low statistical significance between channels 4 and 3 is primarily due to the low number of GRBs with significant fluence in channel 4.

Figure 2 shows graphically the results of a similar test done with more divisions of P_{64}. Instead of breaking the samples up into only 2 groups of high and low peak flux, we broke the public domain sample up into 5 groups. The plot shows that the gross relation between peak flux and hardness is not dominated by particularly bright bursts or by weak bursts near the BATSE sensitivity limit. The brightness-hardness relation is discernable over the whole data sample. We feel this result complements the conclusion reached in the previous section.

4. POSSIBLE SYSTEMATIC ERRORS AND BIASES

The gross spectral difference between the bright and dim GRBs that we have measured could be a property of GRBs themselves. However, it could also be due to systematic errors or biases. Sources of these include biases introduced by BATSE detection thresholds and trigger criteria, statistical fluctuations, assumptions applied to the data analysis, or a combination of these effects. A more detailed discussion of some these possibilities follows.

One concern with a statistic that involves a ratio is that the results are dominated by a few data points where the denominator is near zero (Laros et al. 1984; Schaefer 1993). We have addressed this problem by incorporating the numerator as an additive term in the denominator; this measure results in each contributing term in Eq. (1) being near unity. Next, we have exclusively used statistics that involve a cumulative sum. None of the denominators used in the §2 results were within 2 σ of zero. Thus, we are relatively immune to potential singularities that occur in hardness ratio calculations.

Another concern involves statistical fluctuations in the measurements. An indication that these fluctuations are not important comes from tracking the accumulation of this measurement error (in quadrature) for our public domain results. Here, we have found that our results are extremely significant, usually to better than 25 σ, when measurement error *only* is examined. This error is hence insignificant when compared to fluctuations caused by the differences in spectral properties between sample GRBs themselves.

The hardness difference could also be caused by the fluke inclusion of a small sample of particularly bright, hard bursts or particularly dim, soft bursts which carry unusually high statistical weight. Our choice of H in Eq. 1 was made to minimize this effect. Each term in the Eq. (1) sum is of order unity and has roughly equal statistical weight. Thus, bursts near the bright edge of a brightness group do not dominate the statistics. Figure 2 also shows that the hardness difference is seen over the whole of the public domain sample. To further test for sample variations, the results were recalculated using randomly chosen subsets of the data. These tests did not indicate that such a fluke inclusion effect was operating.

Another concern is that we are testing for a correlation between quantities that are not fully independent. Perhaps P_{64}, whose counts are effected mostly by channel 3, is intrinsically correlated with $H_{3/2}$, whose value might contain a residual proportionality to the counts in channel 3. We argue that the correlation is seen in $H_{4/3}$, $H_{3/2}$ and $H_{2/1}$. Were peak count rate dominated by a single channel (channel 3 for example), one might expect the opposite correlation between P_{64} and $H_{4/3}$ than between peak count rate and $H_{3/2}$. Such an effect is not seen.

The trigger algorithm of the BATSE instrument may introduce a bias into the sample it detected, in which case our result would not be a measure of GRB properties, but instead related to the trigger criteria. BATSE triggers (begins a GRB data accumulation) when the combined counts in channels 2 and 3 for two detectors on either the 64 ms, 256 ms, or 1024 ms time scale are found to exceed 5.5 σ above the background determined from the previous 17 s (Fishman et al. 1989).

One example of such a "trigger bias" for weak bursts is that, statistical fluctuations causing detection may favor GRBs with $H_{3/2}$ near unity and bias the sample toward this value. However, this is harder than the measured results in Figure 1 and could not further soften the dim burst sample. In another example, the trigger criteria demands that counts in channels 2 and/or 3 (which typically have the highest count rates) be above a certain level, but allows arbitrarily low counts in channels 1 and 4. This could introduce a bias against bursts with high counts in 1 and 4 and low counts in 2 and 3 causing a systematic softening in the measured $H_{4/3}$ for dim bursts. However, if this bias were significant it would also cause $H_{2/1}$ to harden, and both effects are not consistent with the statistical softening of bursts detected.

We have tested for several other systematic errors including potential background effects and selection criteria without finding an effect which could successfully mimic the proposed dim/soft correlation claimed. In conclusion, we believe that bias is not responsible for the measured difference in spectral hardness ratios. We therefore assert that the measured gross spectral differences of GRBs originate from properties of the GRBs themselves.

5. DISCUSSION

Could this brightness - hardness correlation be related to bulk special relativistic motion? Perhaps the brighter bursts are being beamed toward us at a significantly higher Lorentz factor. One might then also expect a correlation between duration and spectral hardness - and such a correlation has been reported recently by Kouveliotou et al. (1993). Were SR effects to completely explain the different durations of GRBs, the shortest GRBs would be expected to be seen 3 decades in energy higher than the longest duration GRBs. At first glance, one might conclude that such an effect is not seen - the Kouveliotou et al.

(1993) effect is more modest. However, to rule this out definitively one must run Monte Carlo calculations testing how these great spectral shifts combine with BATSE's trigger criteria.

Could this brightness - hardness correlation be related to cosmology? A redshift of order unity is expected from the number - brightness relation as analyzed by Wickramasinghe et al. (1993), by Fenimore et al. (1993), and by Emslie and Horack (1994). A time-dilation effect of order a factor of two between bright and the dim burst groups has recently been measured by Norris et al. (1993a, 1993b, 1994). That more distant GRBs would have their spectra redshifted relative to nearby GRBs is in the same sense as the observed result. It is therefore possible that the observed hardness - brightness correlation is primarily a result of cosmological expansion of the universe.

Relativistic effects, however, might work in the opposite direction than that proposed above (Turner 1993). A soft GRB with a power-law spectra would have its spectra redshifted an equal amount as a hard GRB, but more energy would be shifted out of BATSE's trigger channels, which could cause it to fall below BATSE's trigger detection threshold. This cosmological effect would work in the opposite direction from what is observed - making detected dim GRBs *harder*.

GRB spectra, however, are not well described by a power law - a fact which underlies the observed difference in hardness ratios. If GRB spectra fall off more rapidly at higher energies, this rapid fall off would also be shifted to the BATSE detection bands, and could mean that some dim GRBS would be measured as *softer* in the shifted energy ranges. To determine the magnitude and even *direction* of this effect, one must run Monte Carlo simulations.

These effects are primarily related to the triggering of GRBs, but, as seen in Figure 2, the brightness-hardness relation is visible even for sets of GRBs significantly above BATSE's triggering threshold. Given our sample completeness with respect to trigger criteria, this artificial threshold should affect each group in the same way.

Some might object to our use of peak count rate as a discriminative attribute of GRBs rather than fluence. For all hardness ratio formulations involving fluence, however, the results were statistically insignificant. This suggests that peak flux is a more discriminative attribute than fluence for GRBs (see also Kouveliotou et al. 1993).

In summary, we have found that within the sample of BATSE-detected bursts, bright GRBs are spectrally harder than dim ones. We believe that this is the first time that fluctuations in the mean hardness caused by the differing properties of bursts in the sample have been specifically addressed in determining the significance of the difference in hardness in GRB brightness subclassses. The cause of the spectral difference is open to question, but it appears that it may be related to the time dilation measured in Norris et al. (1994). We are currently working to determine whether a time dilation consistent with Norris et al. (1994) adequately describes this measured spectral correlation (Bonnell et al. 1994). Our current best guess is that this correlation is cosmological in origin.

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Table 1

Hardness Ratios of First 2 Years of BATSE GRBs

Hardness Channels	H for GRBs P_{64} < median	H for GRBs P_{64} > median	σ difference
2/1	1.34	1.68	5.2
3/2	2.21	3.25	6.8
4/3	1.13	1.39	1.5

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FIGURE CAPTIONS

Figure 1: The boxes depict hardness ratio (channel 3 divided by channel 2) versus time for the bright burst group, while the X's denote hardness versus time for the dim burst group. One sigma errors bars determined from the sample variance are depicted by the crosses.

Figure 2: A plot of hardness ratio in fluence versus peak flux for the first two years of BATSE data (which includes 482 public domain GRBs). Peak flux is taken on the 64-ms time scale. The sample has been broken up into 5 brightness groups. One sigma error bars, determined from the sample variances internal to each brightness group, are shown.