EVIDENCE FOR TWO DISTINCT MORPHOLOGICAL CLASSES OF GAMMA-RAY BURSTS FROM THEIR SHORT TIMESCALE VARIABILITY

D. Q. Lamb, C. Graziani, and I. A. Smith
Department of Astronomy and Astrophysics and Enrico Fermi Institute
University of Chicago, Chicago, IL 60637

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Abstract

We have analyzed the 241 bursts for which peak counts \((C)_{\text{max}}\) exist in the publicly available Burst and Transient Source Experiment (BATSE) catalog. Introducing peak counts in 1024 ms as a measure of burst brightness \(B\) and the ratio of peak counts in 64 and 1024 ms as a measure of short timescale variability \(V\), we find a statistically significant correlation between the brightness and the short timescale variability of \(\gamma\)-ray bursts. The bursts which are smoother on short timescales are both faint and bright, while the bursts which are variable on short timescales are faint only, suggesting the existence of two distinct morphological classes of bursts.

Subject headings: gamma-rays: bursts

1 INTRODUCTION

The Burst and Transient Source Experiment (BATSE) has detected more than 600 \(\gamma\)-ray bursts (Meegan et al. 1993). The BATSE catalogue (Fishman et al. 1993) is the largest homogeneous sample of \(\gamma\)-ray bursts ever assembled and, as such, constitutes a unique resource for studying burst properties. To date, however, no clear correlations between burst properties or distinct morphological classes of bursts have been found.

The Hertzsprung-Russell (H-R) diagram, in which the brightness of a star is plotted versus color (the ratio of the flux in two different energy intervals), proved particularly useful in classifying stars. A striking feature of \(\gamma\)-ray bursts is the diversity of their time histories (see, \textit{e.g.} Fishman et al. 1992). Guided by the success of the H-R diagram for stars and the temporal diversity of \(\gamma\)-ray bursts, we consider an analogous diagram for \(\gamma\)-ray bursts in which we plot a measure of burst brightness versus a variability “color” (the ratio of the peak flux or the peak counts in two different time intervals).
We choose $B \equiv (\bar{C}^{1024})_{\text{max}}$, the expected peak counts in 1024 ms, as our measure of burst brightness because 1024 ms is the longest time interval for which peak counts are given in the publicly available BATSE burst catalogue, and therefore has the best chance of smoothing out effects due to short timescale variability. We choose $V \equiv (\bar{C}^{64})_{\text{max}}/(\bar{C}^{1024})_{\text{max}}$, the ratio of expected peak counts in 64 and 1024 ms, as our measure of short timescale variability because 64 ms is the shortest time interval, and 64 and 1024 ms are the most disparate time intervals, for which peak counts are given in the same catalogue. There are many other possible measures of variability, and better measures may be found from detailed analysis of burst time histories and/or from the acquisition of more data.

Our measure of variability measures an extreme property of the burst (short timescale variability) at a particular moment during the burst (the peak of the burst). Thus it is complementary to global measures of burst variability, such as power spectra (Kouveliotou et al. 1992) and wavelet analyses (Norris et al. 1992, 1993).

2 ANALYSIS

The solid lines in Figure 1 show the time histories of two simulated $\gamma$-ray bursts, defined by $\bar{C}^{64}$, the expected counts in 64 ms. Both bursts have durations $t_{\text{dur}} = 512$ ms; the total period shown in each time history, including background, is 1024 ms. For $\bar{C}^{1024}_{\text{bk}}$, the expected background counts in 1024 ms, we take 2500 counts; this value is typical for the BATSE detector (Meegan et al. 1992). For $(\bar{C}^{1024})_{\text{max}}$, the expected peak counts in 1024 ms for the simulated $\gamma$-ray bursts, we choose 500 counts; this value is typical of the bursts observed by BATSE. Since $t_{\text{dur}} < 1024$ ms for both bursts in Figure 1, $B \equiv (\bar{C}^{1024})_{\text{max}}$ corresponds to the total number of counts in the burst, and is therefore a rough measure of burst fluence; for bursts with $t_{\text{dur}} > 1024$ ms, this is no longer true. The time history of the first simulated burst has a spike of duration $t_{\text{spike}}^{\text{dur}} = 64$ ms, whereas that of the second is flat. The expected peak counts in 64 ms of the two bursts are $(\bar{C}^{64})_{\text{max}} = 200$ and 64 counts, respectively.

We desire $B$ and $V$ as our measures of burst brightness and short timescale variability. However, BATSE observes $B_{\text{obs}} \equiv (C^{1024})_{\text{max}}$ and $V_{\text{obs}} \equiv (C^{64})_{\text{max}}/(C^{1024})_{\text{max}}$, where $(C^{64})_{\text{max}}$ and $(C^{1024})_{\text{max}}$ are the peak counts in 64 and 1024 ms, respectively. The latter differ from the former because the time history observed by BATSE differs from the expected time history of the burst due to Poisson fluctuations. The dashed lines in Figure 1 are examples of the time histories that BATSE might actually observe for the two bursts.

Figure 2 (top panel) shows the distribution of burst brightness $B_{\text{obs}}$ versus short timescale variability $V_{\text{obs}}$ for the 201 bursts in the publicly available BATSE catalogue for which
both \((C^{64})_{\text{max}}\) and \((C^{1024})_{\text{max}}\) exist. The \(V_{\text{obs}}\)-distribution is not independent of \(B_{\text{obs}}\). In particular, there are almost no bursts in the upper right quadrant and in a small, triangular-shaped region in the lower left hand corner of the diagram.

By definition, the \((C)_{\text{max}}\) protocol selects the largest \(C^{64}\) and \(C^{1024}\) during the burst, irrespective of the other. Thus \((C^{64})_{\text{max}}\) need not come from the time interval corresponding to \((C^{1024})_{\text{max}}\) (nevertheless, one can show that \(1/16 \leq V_{\text{obs}} \leq 1\)). Consider for illustrative purposes the limiting case of a flat burst; i.e., a burst for which \((C^{64})_{\text{max}} = \bar{C}^{64}\) is constant.

If \(t_{\text{dur}} \leq 64\) ms, there is only one \(C^{64}\) during the burst. Although \((C^{64})_{\text{max}} = \bar{C}^{64}\) may differ from \((C^{64})_{\text{max}}\) due to Poisson fluctuations, it equals it, on average. If \(t_{\text{dur}} > 64\) ms, there are several \(C^{64}\) during the burst, all of which differ from \((C)_{\text{max}}\) due to Poisson fluctuations. Since the \((C)_{\text{max}}\) protocol selects the largest of \(C^{64}\), it is likely that \((C^{64})_{\text{max}}\) exceeds \((C^{64})_{\text{max}}\) (see Figure 1). Thus \((C^{64})_{\text{max}}\) is a biased estimator of \((C^{64})_{\text{max}}\) if \(t_{\text{dur}} > 64\) ms (Meegan 1993, private communication). Similarly, \((C^{1024})_{\text{max}}\) is a biased estimator of \((C^{1024})_{\text{max}}\). We must remove this “Meegan bias” before evaluating the significance of the pattern in the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram.

We have investigated the Meegan bias in detail (Lamb, Boorstein, and Graziani 1993). The bias maps the \((B, V)\)-diagram onto the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram. However, the map is not invertible because of the Poisson fluctuations of \((C^{64})_{\text{max}}\) and \((C^{1024})_{\text{max}}\), respectively; rather, it tends to shift \(B\) and \(V\) to larger values of \(B_{\text{obs}}\) and \(V_{\text{obs}}\), and smears them out. Our studies show that the bias in \(V_{\text{obs}}\) is zero for a burst whose duration \(t_{\text{dur}} \leq 64\) ms, or a burst whose duration \(t_{\text{dur}}\) is arbitrarily long but which has a spike whose duration \(t_{\text{dur}}^{\text{spike}} \leq 64\) ms. The bias in \(V_{\text{obs}}\) increases until \(t_{\text{dur}}^{\text{spike}}\) (or \(t_{\text{dur}}^{\text{spike}}\)) reaches 1024 ms. For longer bursts, the bias increases very slowly because the ratio of the number of \((C^{64})_{\text{max}}\) samples to the number of \((C^{1024})_{\text{max}}\) samples remains \(\approx 16\). Thus, the bias for \(t_{\text{dur}}^{\text{spike}} = 1024\) ms closely approximates the maximum bias for any \(t_{\text{dur}}\) or \(t_{\text{dur}}^{\text{spike}}\).

We remove the Meegan bias using an approximate method based on a number of simplifying assumptions. First, we neglect the bias in \(B_{\text{obs}} \equiv (C^{1024})_{\text{max}}\), which is relatively small. Second, we assume that the time history of the burst or of the spike during the burst, is flat; in this limiting case, \((C^{64})_{\text{max}} = \bar{C}^{64}\) and \(t_{\text{dur}}^{\text{spike}} = 64 V_{\text{obs}}^{-1}\) ms. The bias is maximal for this model, as noted earlier; any difference that remains between the \(V\)-distributions for faint and bright bursts therefore cannot be due to bias. Third, we adopt the bias for the minimum of \(t_{\text{dur}}^{\text{spike}} = 64 V_{\text{obs}}^{-1}\) ms and 1024 ms, which closely approximates the maximum bias for

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1We have omitted from our analysis four additional bursts (trigger ID numbers 414, 486, 508, and 1346) for which the \((C^{64})_{\text{max}}\) or \((C^{1024})_{\text{max}}\) listed in the publicly available BATSE catalogue are erroneous (Howard 1993, private communication).
any \( t_{\text{dur}} \) or \( t^{\text{spike}} \). Fourth, we assume that the bias maps a point in the \((B, V)\)-diagram onto a unique point in the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram; \( i.e. \), that the bias map is a \( \delta \)-function. This is only approximately true because of the variances of \((C_{64}^{\text{max}})\) and \((C_{1024}^{\text{max}})\) about \((\bar{C}_{64})\) and \((\bar{C}_{1024})\). These four simplifying assumptions enable us to invert the bias, and map bursts in the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram onto points in the \((B, V)\)-diagram.

Figure 2 (middle panel) shows contours of constant \( V \) in the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram, taking for the expected background counts in 1024 ms \( C_{\text{bk}}^{1024} = 2500 \) counts, a value which is typical for the BATSE detectors. The bias is zero along the top of the diagram. Elsewhere, the bias is least in the upper right hand corner and greatest in the lower left hand corner of the diagram. This pattern arises partly from the time variability of the bursts, which is greatest along the top of the diagram and least along the bottom, and partly from the relative variances in the total counts \( C_{\text{bk}} + (C_{64}^{\text{max}}) \) and \( C_{\text{bk}} + (C_{1024}^{\text{max}}) \), which are least in the upper right hand corner of the diagram and greatest in the lower left hand corner.

Bursts that lie below the \( V = 1/16 \) contour (shown as a solid line) in the lower left hand corner of the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram would map onto points below \( V = 1/16 \) in the \((B, V)\)-diagram, which is unphysical. This is due to our assumption that the burst time history is flat, for which the bias is maximal, and to our \( \delta \)-function approximation for the bias map. We therefore place a “floor” at \( V = 1/16 \) in the \((B, V)\)-diagram, and do not allow points mapped from the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram to go below it.

3 RESULTS

Figure 2 (bottom panel) shows the resulting distribution of bursts in the \((B, V)\)-diagram. The statistical errors in \( B \) and \( V \) are a function only of location in the \((B, V)\)-diagram; we show them for six representative locations. The empty triangular region at the lower left hand corner of the \((B_{\text{obs}}, V_{\text{obs}})\)-diagram has disappeared; it may therefore be the result of Meegan bias. In contrast, the presence of bursts in the upper left hand quadrant and the absence of bursts in the upper right hand quadrant of the diagram remain. This means that there is a lack of bursts that are bright (in 1024 ms) and have a bright, short spike (either during the bright 1024 ms or elsewhere during the burst).

To evaluate the significance of the pattern, we use three \( \chi^2 \) tests for binned data which address the question of whether or not two distributions have similar shapes, irrespective of scale, \( i.e. \), irrespective of the total number of objects in each histogram. The first is the “T-test” of Eadie et al. (1971), in which the scales of the two histograms are set at their maximum likelihood best-fit values. The second is the two-histogram test described in Numerical Recipes (Press et al. 1986), with the histogram having the smaller number of
TABLE 1

HISTOGRAMS OF FAINT, BRIGHT, SMOOTH, AND VARIABLE BURSTS

| Sample  | Two Bin | Three Bin |
|---------|---------|-----------|
|         | Bin 1   | Bin 2     | Bin 1 | Bin 2 | Bin 3 |
| Faint   | 135     | 27        | 126   | 19    | 17    |
| Bright  | 38      | 1         | 38    | 0     | 1     |
| Smooth  | 131     | 33        | 81    | 73    | 10    |
| Variable| 36      | 1         | 28    | 8     | 1     |

objects scaled up so that both histograms have the same number of objects. The third is an adaptation of the previous test in which the scale of the histogram with the smaller number of objects is allowed to vary so as to minimize $\chi^2$.

We divide the bursts into those which are faint (log $B \leq 3.28$) and bright (log $B > 3.28$), and construct histograms having two and three equal logarithmic bins in variability between log $V = -1.2$ and 0. We also divide the bursts into those which are smooth (log $V \leq -0.8$) and variable (log $V > -0.8$) on short timescales, and construct histograms having two and three equal logarithmic bins in brightness between log $B = 2$ and 4.7. Table 1 gives the numbers of bursts in each bin of these histograms, and Table 2 lists the results of the three tests. The Q-values range from $2.2 \times 10^{-2}$ to $3.5 \times 10^{-6}$, comparing the variability of faint and bright bursts, and from $1.5 \times 10^{-2}$ to $7.8 \times 10^{-5}$, comparing the brightness of smooth and variable bursts.

The disparity between the results of the three tests is due primarily to the small number of bursts in some histogram bins (see footnote 2). We therefore also evaluate the significance of the correlation in the $(B,V)$-diagram using a statistical test which compares the mean variabilities of faint and bright bursts, or the mean brightnesses of smooth and variable bursts, and evaluates the significance of the differences between the means using a $t$-test (Press et al. 1986). This test is particularly suitable to the situation at hand because it implicitly takes into account the uncertainty in the location of each burst in the $(B,V)$-diagram and, unlike $\chi^2$ tests, does not require binning the data, which can necessitate the

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2The results are similar for histograms with more bins. However, the results are increasingly suspect because the number of bursts becomes small in many histogram bins, necessitating the use of Poisson rather than Gaussian statistics and invalidating the use of the $\chi^2$ distribution for calculating statistical significance.
**TABLE 2**

**COMPARISON BETWEEN FAINT AND BRIGHT, AND SMOOTH AND VARIABLE BURSTS**

| Statistical Test | Faint vs. Bright | Smooth vs. Variable |
|------------------|------------------|---------------------|
|                  | 2 Bins | 3 Bins | 2 Bins | 3 Bins |
| **χ²**          | **χ²** | **χ²** | **χ²** | **χ²** |
| **Q-value**     | **Q-value** | **Q-value** | **Q-value** | **Q-value** |
| **T-Test**      | 5.2    | 8.3   | 6.5    | 8.4     |
| **χ²**          | 2.2 × 10⁻² | 1.6 × 10⁻² | 1.0 × 10⁻² | 1.5 × 10⁻² |
| **Q-value**     | 3.3 × 10⁻² | 3.1 × 10⁻² | 6.4 × 10⁻³ | 1.2 × 10⁻² |
| **Fixed Scale** | 12     | 25    | 16     | 10      |
| **T-Test**      | 12     | 25    | 16     | 10      |
| **χ²**          | 4.2 × 10⁻⁴ | 3.5 × 10⁻⁶ | 4.9 × 10⁻⁵ | 6.4 × 10⁻³ |
| **Q-value**     | 3.7 × 10⁻⁶ | 8.9 × 10⁻⁵ | 1.2 × 10⁻² |
| **Variable Scale** | 12 | 25 | 16 | 10 |
| **T-Test**      | 12     | 25    | 16     | 10      |
| **χ²**          | 5.1 × 10⁻⁴ | 3.7 × 10⁻⁶ | 7.8 × 10⁻⁵ | 8.9 × 10⁻⁵ |
| **Q-value**     | 3.7 × 10⁻⁴ | 8.9 × 10⁻⁵ | 1.2 × 10⁻² |

*a* Two-histogram “T-test” (Eadie et al. 1971).

*b* Two-histogram test (Press et al. 1986).

*c* Adaptation of two-histogram test in Press et al. (1986) (see text).

We find that the faint \((B \leq 1900)\) bursts have a mean short timescale variability \(\log V = -0.97 \pm 0.026\) whereas the bright \((B > 1900)\) bursts have \(\log V = -1.05 \pm 0.028\). Thus the difference of the means divided by their combined variance is 2.2, corresponding to a \(Q\)-value of \(3.3 \times 10^{-2}\). We find that the smooth bursts have a mean brightness \(\log B = 2.99 \pm 0.036\) whereas the variable bursts have \(\log B = 2.67 \pm 0.059\). Thus the difference of the means divided by their combined variance is 4.5, corresponding to a \(Q\)-value of \(4.6 \times 10^{-5}\).

We conclude that the difference in short timescale variability between faint and bright \(\gamma\)-bursts, and the difference in brightness between bursts that are smooth and variable on short timescales are significant.

We have checked our results in two ways. First, we determined the number of bursts in our study which have gaps in their time histories, due to malfunctioning of the Compton Observatory tape recorders. Using the comments table in the publicly available BATSE catalogue, we find that 25 of the 48 bursts with data gaps are among the bursts we have used. Of these 25, 21 are faint and 4 are bright bursts; three of the faint bursts and none of the bright bursts are variable on short timescales. We conclude that gaps in the time histories of the bursts cannot account for our results.

Second, we inspected the time histories of the 30 individual bursts out of the 201 bursts in our sample for which time histories are publicly available. Of these, 17 are faint and 13...
are bright bursts; five of the faint bursts and one of the bright bursts are variable on short timescales. In all cases, we were able to verify from inspection of the time history that the location of the burst in the $(B, V)$-diagram is correct.

4 DISCUSSION

The correlation between the brightness $B$ and the short timescale variability $V$ of $\gamma$-ray bursts might imply strong source evolution, or it might reflect the existence of two distinct classes of $\gamma$-ray bursts. One class might be bursts that exhibit a range of short timescale variability ($-1.2 \leq \log V \leq 0$) and are faint, and the other might be bursts that are smooth on short timescales ($\log V \leq -0.8$) and bright. Alternatively, one class might be bursts that are smooth on short timescales ($\log V \leq -0.8$) and range from faint to bright, and the other might be bursts that are variable on short timescales ($\log V > -0.8$, corresponding to $t_{\text{dur}}$ or $t_{\text{spike}} \approx 0.3$ s) and faint. Clearly, other decompositions are also possible.

Using only the correlation between $B$ and $V$ presented here, we cannot distinguish between these various possibilities. However, in subsequent papers, we report statistically significant evidence that the correlation between $B$ and $V$ reflects the existence of two distinct morphological classes of $\gamma$-ray bursts: Type I bursts, which are smooth on short timescales ($\approx 0.3$ s) and range from faint to bright, and Type II bursts, which are variable on short timescales and faint. Type I bursts also have longer durations and softer spectra (Lamb and Graziani 1993a), and a flatter brightness distribution (Lamb and Graziani 1993b) than do Type II bursts. The dashed lines in the top and bottom panels of Figure 2 correspond to $\log V = -0.8$, the cut in variability which separates the two classes. Because we have removed the Meegan bias assuming that burst time histories are flat, for which the bias is maximal, it is likely that we have placed some bursts which are variable on short timescales in the smooth class, but not vice-versa.

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Figure 1: Time histories of two simulated $\gamma$-ray bursts, each lasting $t_{\text{dur}} = 512$ ms. (left panel) Burst with a spike in $\bar{C}_{64}^4$ lasting $t_{\text{spike}} = 64$ ms. (right panel) Burst with $\bar{C}_{64}^4$ equal to a constant. The solid histograms show $\bar{C}_{64}^4$, the expected counts per 64 ms; the dashed histograms show $C_{64}^4$, the observed counts per 64 ms. Also labeled are $(\bar{C}_{64}^4)_{\text{max}}$, the expected peak counts per 64 ms, and $(C_{64}^4)_{\text{max}}$, the observed peak counts per 64 ms.

Figure 2: (top panel) Distribution of 201 bursts in the $(B_{\text{obs}}, V_{\text{obs}})$-diagram. (middle panel) Contours of constant $V$ in the $(B_{\text{obs}}, V_{\text{obs}})$-diagram. (bottom panel) Distribution of 201 bursts in the $(B, V)$-diagram. The filled and open circles in the $(B_{\text{obs}}, V_{\text{obs}})$- and $(B, V)$-diagrams denote bursts detected by the 1024 ms trigger and by the 256 or 64 ms triggers, respectively. The solid lines in the $(B_{\text{obs}}, V_{\text{obs}})$- and $(B, V)$-diagrams correspond to $V = 1/16$, the minimum possible variability, while the dashed lines correspond to $\log V = -0.8$, the cut in variability which separates the bursts into two distinct classes.