STATISTICS OF GAMMA RAY BURST TEMPORAL ASYMMETRY

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ABSTRACT

We study the temporal asymmetry of over 600 bursts from the BATSE 3B catalog, encompassing a 200-fold range in peak flux. By comparing the rates of rise and fall of the flux near the highest burst peak, we find that about two-thirds of the bursts exhibit a preferred asymmetry in the sense that the flux rises more rapidly than it falls, confirming the conclusions of previous studies employing smaller databases. The statistical significance of the average time asymmetry of the sample is $> 99.999\%$; therefore, models that predict time symmetry of the burst profile are ruled out. We find no statistically significant correlation between burst temporal asymmetry and peak. This result is consistent with both cosmological and local interpretations of the gamma ray burst phenomenon.
1. INTRODUCTION

The origin of gamma ray bursts (GRBs) remains a mystery since their detection by the Vela satellites in July 1969 (Klebesadel, Strong, & Olson 1973). The Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory continues to detect GRBs distributed with striking isotropy on the sky, and with a dearth of faint events compared to that expected for a homogeneous distribution (Meegan et al. 1992; Briggs et al. 1996). With counterparts at other wavelengths yet to be identified, the distances to GRBs remain uncertain. The idea that GRBs originate at cosmological distances has emerged as a serious possibility, while the prospect that bursts originate within the halo of the Galaxy remains tenable. In the face of these uncertainties, the identification and interpretation of fundamental properties of GRB variability is needed to assess proposed models.

Cosmological GRB models account naturally for the observed isotropy while explaining the dearth of faint events as due to a modification of the observed distribution by the universal expansion. These models also predict a general time dilation of the more distant, fainter events. Recently, some authors have found indications of time dilation consistent with cosmic expansion (see, e.g., Norris et al. 1994; Norris 1994; Davis et al. 1994; Fenimore & Bloom 1996), but the evidence is not yet statistically compelling. Models in which GRBs originate near the Galaxy have the appeal of modest luminosity requirements compared to cosmological models, but need fine tuning to maintain consistency with the observed isotropy and number-flux relationship.

Some GRB models, such as those accounting for burst time structure as due solely to beams crossing our line of sight, predict time-symmetric light curves. Recent quantitative studies of the shapes of GRB light curves, however, have established that GRBs are time-asymmetric (Link, Epstein, & Priedhorsky 1993; Norris et al. 1993; Nemiroff et al. 1994; Mitrofanov et al. 1994; Fishman 1994), confirming earlier claims (see, e.g., Barat et al.
Link, Epstein, & Priedhorsky (1993) utilized a skewness function, similar to that used by Weisskopf et al. (1978), and found that the majority of 20 bright GRBs selected from the first 48 detected by BATSE are time-asymmetric in the sense that the flux rises more rapidly than it falls. In a subsequent study, Nemiroff et al. (1994) quantified the degree of time asymmetry by considering the ratio of the number of times where the counts in a given time bin are lower than in the previous bin to the number of the times the counts are higher. Nemiroff et al. (1994) studied about 40 bright bursts, and confirmed with high statistical significance the result found by Link, Epstein, & Priedhorsky (1993). Mitrofanov et al. (1994) constructed an average light curve from 260 bursts that showed a quickly rising flux followed by a slower decay. The results of these studies exclude models that predict time-symmetric GRB light curves.

Inasmuch as temporal asymmetry is independent of burst duration and intensity, it is a useful statistic to compare with other burst properties. The purpose of this paper is to study temporal asymmetry for a sample of bursts encompassing a large range in peak flux, and to test for a correlation between temporal asymmetry and peak flux. The discovery of a correlation would provide evidence for evolutionary or cosmological effects, though the lack of such a correlation would not necessarily constitute evidence against the cosmological interpretation. We find that approximately two-thirds of bursts spanning a 200-fold range in peak flux exhibit the same temporal asymmetry, with no statistically significant correlation between the asymmetry and the peak flux.

In §2 we describe the analysis techniques we use in studying burst temporal asymmetry and the attributes of the data set tested. In §3 we discuss our results, and in §4 we summarize our results and their implications.
2. ANALYSIS

As a measure of the shape of GRB light curves, we define a time-asymmetry parameter as the third-moment of the burst time profile:

\[ A \equiv \frac{\langle (t - \langle t \rangle)^3 \rangle}{\langle (t - \langle t \rangle)^2 \rangle^{3/2}}, \]  

where \( \langle \rangle \) denotes an average over the data sample performed as:

\[ \langle f(t) \rangle \equiv \frac{\sum_i (c_i - c_{th}) f(t_i)}{\sum_i (c_i - c_{th})}. \]  

Here \( c_i \) is the measured number of counts in the \( i \)th bin, \( t_i \) is the time of the \( i \)th bin, and \( c_{th} \) is a threshold count level. The time-asymmetry parameter is calculated for a contiguous data sample including the burst peak and nearby bins in which the counts exceed \( c_{th} \). We define the threshold as

\[ c_{th} \equiv f(c_p - b) + b, \]  

where \( c_p \) is the peak count rate, \( b \) is the background, and \( f(< 1) \) is a fraction that will be fixed for each data set. For a given \( f \), this definition of the threshold ensures that \( A \) is calculated to the same fraction of the peak flux, relative to the background, for each burst in the data sample. Larger values of \( f \) emphasize the structure of the peak over that of the surrounding foothills. The normalization of \( A \) has been chosen in such a way as to make it independent of burst amplitude, duration and background. For a time-symmetric burst peak, \( A = 0 \), and \( A > 0 \) \((< 0)\) for a burst whose flux rises (falls) more quickly than it falls (rises). For an infinitely fast rise followed by an exponential decay, \( A = 2 \), independent of the time-constant of the decay.

3. RESULTS

In Fig. 1 we show the burst time-asymmetry parameter \( A \) as a function of peak flux for 631 bursts from the BATSE 3B catalog, selected as described below. Our sample
contains faint bursts as well as bright ones, spanning a 200-fold range in peak flux. We use the BATSE PREB plus DISC data types at 64 ms time resolution, with the four energy channels 25-50 keV, 50-100 keV, 100-300 keV, and > 300 keV combined to attain the best statistics. For each burst, $A$ was calculated for a contiguous sample of data containing the highest burst peak and for which each bin satisfies $c_i \geq c_{th}$. The only requirement for a burst to be tested is that the data sample satisfying $c_i \geq c_{th}$ contain at least three bins.

The error bars in Fig. 1 represent one-$\sigma$ deviations from the calculated time asymmetry due to photon counting statistics; they were obtained by randomizing the measured counts according to Poisson statistics and calculating the variance of the time-asymmetry parameter for many trials. A preponderance of positive time asymmetries is apparent in Fig. 1 for all peak fluxes; about two-thirds of the bursts have positive time asymmetry. In Table 1 we show the weighted average of the time-asymmetry parameter for different values of $f$. The small values of the standard deviation in Table 1 show that the positive time asymmetry is not an artifact of Poisson noise. To estimate the statistical significance of the positive time asymmetry, we consider the probability that the observed fraction of positive $A$ bursts occurs by chance. For example, for our largest sample in Table 1 containing 631 bursts, 68% of the bursts have positive temporal asymmetry. If $A$ is a random variable of zero mean, the probability of such a high percentage of $A > 0$ bursts occurring by chance is $\lesssim 0.001\%$.

While most bursts have positive time asymmetry, there are numerous counterexamples. Examples of bursts with positive and negative $A$ are shown in Fig. 2. Quite often the $A > 0$ events have a simple structure of rapid rise followed by slow decline, while the $A < 0$ events have multiple peaks, as illustrated in the figure. This result is consistent with the conclusion of Bhat et al. (1994) that bursts with more complex structure are less frequent.

In Fig. 1 it appears that time asymmetry increases with peak flux. Is this apparent
trend statistically significant? In Table 2 we show the number-averages of $A$ computed for the bright and dim halves of the sample. For our largest data set ($f = 0.1$), $A_{\text{bright}}/A_{\text{dim}}$ is $\sim 2$; for larger values of $f$, the ratio is larger. However, because noise has zero average time asymmetry, we expect fainter events, which have lower signal to noise than bright events, to exhibit $A$ values closer to zero. To estimate the significances of the $A_{\text{bright}}/A_{\text{dim}}$ values found, we studied how the $A$ values of the bright half of bursts change upon degrading them to fainter peak fluxes. With each burst in the bright half of the sample, we identified a peak flux selected at random from the dim half. Each bright burst was then degraded by reducing the counts in each bin by a factor of the peak count rate of the selected dim burst to the peak count rate of the bright burst, $c_{p, \text{dim}}/c_{p, \text{bright}}$. To each bin in this simulated dim burst, we added a Poisson-deviate with a mean of the new number of counts. In this way we produced simulated dim bursts with the same intrinsic temporal asymmetry as the bright bursts. To estimate the significances of the ratios $A_{\text{bright}}/A_{\text{dim}}$ in Table 2, we produced numerous simulated data sets, calculated the ratio for each simulation, and determined the frequency with which the simulated $A_{\text{bright}}/A_{\text{dim}}$ exceeded the value from the real data set. The simulated value of $A_{\text{bright}}/A_{\text{dim}}$ exceeded the value measured from the real data set in 39% to 56% of the simulations, depending on $f$. We conclude that the apparent trend of $A$ with brightness in the BATSE 3B catalog is not statistically significant.

4. SUMMARY AND CONCLUSIONS

We have applied a simple measure of burst temporal asymmetry to a large, uniform sample of bright and dim bursts. About two-thirds of GRBs have time-asymmetric

\footnote{Computing weighted averages $\bar{A}$ in the bright and dim halves of the data set also shows no statistically significant dependence of $A$ on peak flux.}
peaks in the sense that the flux rises more rapidly than it falls, confirming the results of previous analyses of bright bursts (Link, Epstein, & Priedhorsky 1993; Nemiroff et al. 1994; Mitrofanov et al. 1994). We conservatively estimate the significance of the preferred time asymmetry at over 99.999%, thus excluding GRB models that predict time-symmetric light curves. We find that the preferred time asymmetry shows no significant dependence on peak flux. This result is consistent with both cosmological and local interpretations of the GRB phenomenon.

It is a pleasure to thank E. E. Fenimore and J. S. Bloom for providing us with data from the BATSE 3B catalog in a form convenient for this analysis. This work was performed under the auspices of the U.S. Department of Energy, and was supported in part by NASA EPSCoR grant #291471.
Fig. 1.— Burst time-asymmetry parameter $A$ for 631 GRBs. The threshold was chosen by taking $f = 0.1$. Error bars represent one-$\sigma$ deviations of $A$ from the measured values. The vertical line divides the bright half of the sample from the dim half.

Fig. 2.— Examples of bursts of positive temporal asymmetry (a), and negative temporal asymmetry (b).
Table 1. Burst Time Asymmetry

| $f$ | sample size | events with $A > 0$ | $\overline{A}^a$ | $\sigma$ | confidence |
|-----|-------------|---------------------|------------------|---------|------------|
| 0.1 | 631         | 68%                 | 0.14             | 0.00041 | 99.9993    |
| 0.2 | 603         | 66%                 | 0.092            | 0.00048 | 99.99      |
| 0.5 | 463         | 62%                 | 0.086            | 0.0013  | 99.1       |
| 0.67| 350         | 59%                 | 0.12             | 0.0024  | 91         |

$^a$Weighted averages, $\overline{A} \equiv \sum_i A_i \sigma_i^{-2} / \sum_i \sigma_i^{-2}$, where the variance is $\sigma^2 = (\sum \sigma_i^{-2})^{-1}$
Table 2. Average Time Asymmetry – Bright vs. Dim Bursts

| f  | $A_{\text{bright}}/A_{\text{dim}}$ | likelihood |
|----|----------------------------------|------------|
| 0.1| 1.7                              | 56%        |
| 0.2| 2.0                              | 39%        |
| 0.5| 2.7                              | $\sim 50\%$|

$^a$Number averages are calculated by giving equal weights to all data points, i.e., $A_{\text{bright}} \equiv N^{-1} \sum_{\text{bright}} A_i$.

$^b$Likelihood that the quoted $A_{\text{bright}}/A_{\text{dim}}$ is spurious, based on the percentage of simulations yielding values of $A_{\text{bright}}/A_{\text{dim}}$ greater than the quoted value.
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time-asymmetry $A$

peak flux (photons cm$^{-2}$ s$^{-1}$)
