Temporal properties of the short gamma-ray bursts

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Abstract. A temporal analysis has been performed on a sample of 100 bright gamma-ray bursts (GRBs) with $T_{90}<2\,$s from the BATSE Current Catalog. The GRBs were denoised using a median filter and subjected to an automated pulse selection algorithm as an objective way of identifying the effects of neighbouring pulses. The rise times, fall times, FWHM, pulse amplitudes and areas were measured and the frequency distributions are presented here. All are consistent with lognormal distributions. The distribution of time intervals between pulses is not random but consistent with a lognormal distribution. The time intervals between pulses and pulse amplitudes are highly correlated with each other. These results are in excellent agreement with a similar analysis that revealed lognormal distributions for pulse properties and correlated time intervals between pulses in bright GRBs with $T_{90}>2\,$s. The two sub-classes of GRBs appear to have the same emission mechanism which is probably caused by internal shocks. They may not have the same progenitors because of the generic nature of the fireball model.

Key words. Gamma rays – bursts: Gamma rays – observations: Methods – data analysis: Methods – statistical

1. Introduction

It has been recognised that GRBs may occur in two sub-classes based on spectral hardness and duration with $T_{90}>2\,$s and $T_{90}<2\,$s (Kouveliotou et al., 1993; Dezalay et al., 1993; Paciesas et al., 2001). The bimodal distribution can be fit by two Gaussian distributions in the logarithmic durations (McBreen et al., 1994). There is significant evidence for a third subgroup as part of the long duration GRBs (Mukherjee et al., 1998; Horvath, 1998) but this has been questioned because of a possible BATSE selection effect (Hakkila et al., 2000). It has been suggested (Cline et al., 1999) that the small group of GRBs with $T_{90}<0.1\,$s form an additional category. The short GRBs have a higher value of $(V/V_{\text{max}})$ (Katz & Canel, 1996), a much smaller value of the spectral lag (Norris et al., 2000), a pulse shape that depends on position in the burst (Gupta et al., 2000) and a smaller space density than long GRBs (Schmidt, 2001).

A variety of statistical methods have been applied to the temporal properties of GRBs with $T_{90}>2\,$s. It is important to compare the temporal profiles of the long and short GRBs to determine the similarities and differences between the two classes in an objective way. A detailed objective analysis has been performed on the temporal profiles of a large sample of 319 bright GRBs with $T_{90}>2\,$s (Quilligan et al., 2001; Hurley et al., 1998). The properties of the pulses in GRBs and the time intervals between them were found to be consistent with lognormal distributions. These results can be used as templates for comparison with a similar analysis of GRBs with $T_{90}<2\,$s.

The analysis method is presented in section 2 and the results in section 3. In section 4 the results are discussed and compared with the sample of long GRBs.

2. Data Preparation

The dataset was taken from the BATSE current catalog. The time tagged event data at 5 ms resolution was used. The data from the four energy channels were combined into a single channel to maximise the signal to noise ratio. A subset of the current catalogue was selected with GRB durations less than two seconds ($T_{90}<2\,$s). These GRBs were ordered according to their peak flux in 256 ms ($P_{256\text{ms}}$) and the first 100 bursts without data gaps and with 5 ms data available for the complete burst were selected. All GRBs in the sample had $P_{256\text{ms}}>1.6\,$photons cm$^{-2}\,$s$^{-1}$.

2.1. Background subtraction

The first step in the data preparation involved selecting the appropriate background for subtraction. The start and end times for each burst were identified. A background section was then identified which was usually after the main section of the GRB. If 5 ms data was available for the background level estimation, it was used, otherwise a
The standard deviation \( \sigma \) of the number of pulses with \( \tau \geq 5 \) is given in Fig. 1. The median value of the number of pulses per GRB is 2.5 and is smaller than the value of 6 for long GRBs (Quilligan et al., 2001). The distributions of rise time \( t_r \), fall time \( t_f \) and full width at half maximum (FWHM) for the isolated pulses are presented in Fig. 2 along with the lognormal fits to the data. The distributions of pulse amplitudes and areas are presented in Fig. 3 for the isolated pulses. The distribution of time intervals between pulses with \( \tau \geq 5 \) is given in Fig. 4.

The median values and the parameters of the lognormal fits are presented in Table 1. The Kolmogorov-Smirnov (KS) test was used to indicate the effects of varying \( \tau \) and \( \tau \). The pulse property distributions at \( \tau \geq 5 \) and \( \tau \geq 50\% \) were compared with the distributions selected over large range of \( \tau \) and \( \tau \). The significance level probabilities from the KS test for the comparison are presented in Table 1 for \( \tau \geq 3, \tau \geq 20\% \) and \( \tau \geq 8, \tau \geq 80\% \) and all have acceptable values. It was found that when \( \tau \) increased the pulses become less contaminated by overlaps from adjacent pulses.

### 3. Results

#### 3.1. Distributions of \( t_r, t_f, \text{ FWHM, pulse area, pulse} \) amplitude and \( \Delta T \)

The distribution of the number of pulses with \( \tau \geq 5 \) is given in Fig. 1. The median value of the number of pulses per GRB is 2.5 and is smaller than the value of 6 for long GRBs (Quilligan et al., 2001). The distributions of rise time \( t_r \), fall time \( t_f \) and full width at half maximum (FWHM) for the isolated pulses are presented in Fig. 2 along with the lognormal fits to the data. The distributions of pulse amplitudes and areas are presented in Fig. 3 for the isolated pulses. The distribution of time intervals between pulses with \( \tau \geq 5 \) is given in Fig. 4.

The median values and the parameters of the lognormal fits are presented in Table 1. The distribution of the pulse asymmetry ratios, \( t_f/t_r \), is not presented but the values are listed in Table 1. The pulse fall time is generally longer than the rise time. The widths or ranges of the lognormal distributions at the \( \pm 50\% \) are also given in
The major result is that pulses in GRBs with $T_{90}<2$ s have very similar distributions of $t_r$, $t_t$, FWHM, pulse amplitude, pulse area and $\Delta T$. The frequency distributions are broad and all are compatible with lognormal distributions, and at the 50% level span an order of magnitude in the particular pulse property (Table 1). The same pulse properties in GRBs with $T_{90}>2$ s are also well described by lognormal distributions (Quilligan et al., 2001). The results of the correlation analysis on the GRBs and the properties of the pulses (Table 2) are generally in good agreement between long and short GRBS. The main difference is the pulse amplitude because it is not anticorrelated with $t_r$, $t_t$ and FWHM. In GRBs with $T_{90}>2$ s the values of $\Delta T$ are not random but consistent with a lognormal distribution with a Pareto-Levy tail for a small number of long time intervals in excess of 15 s. It was also found that the values of $\Delta T$ were correlated over most of the GRBs and up to more than 20 pulses in the GRBs with large numbers of pulses. In short GRBs there is a strong correlation between the values of $\Delta T$ and also between the pulse amplitudes (Table 3) but the latter are better correlated in GRBs with large number of pulses. In short GRBs there is a strong correlation between the values of $\Delta T$ and also between the pulse amplitudes (Table 3) but the latter are better correlated in GRBs with large number of pulses. In short GRBs there is a strong correlation between the values of $\Delta T$ and also between the pulse amplitudes (Table 3) but the latter are better correlated in GRBs with large number of pulses.

Table 2. Spearman Rank Order correlation coefficients $\rho$ and associated probabilities between a range of burst (first 3 rows) and pulse parameters (second 10 rows).

| Properties                        | $\rho$   | Probability |
|-----------------------------------|----------|-------------|
| No. of Pulses vs. $T_{90}$        | 0.18     | 0.073       |
| No. of Pulses vs. Total Fluence   | 0.38     | $9.8 \times 10^{-5}$ |
| $T_{90}$ vs Total Fluence         | 0.21     | 0.037       |
| Rise Time vs. Fall Time           | 0.54     | $2.7 \times 10^{-10}$ |
| Rise Time vs. FWHM               | 0.79     | $1.3 \times 10^{-10}$ |
| Rise Time vs. Area                | 0.59     | $3.3 \times 10^{-10}$ |
| Rise Time vs. Pulse Amplitude     | 0.013    | 0.90        |
| Fall Time vs. FWHM               | 0.75     | $2.6 \times 10^{-33}$ |
| Fall Time vs. Area                | 0.64     | $2.0 \times 10^{-12}$ |
| Fall Time vs. Pulse Amplitude     | 0.078    | 0.45        |
| FWHM vs. Area                    | 0.60     | $6.89 \times 10^{-11}$ |
| FWHM vs. Pulse Amplitude         | $-0.05$  | 0.64        |
| Area vs. Pulse Amplitude         | 0.65     | $1.1 \times 10^{-12}$ |

Table 3. The Spearman correlation coefficients $\rho$ and probabilities for $\Delta T$s (first 2 rows) and PAs (second 2 rows). The first and third rows refer to adjacent $\Delta T$s and PAs while the second and fourth rows refer to $\Delta T$s or PAs separated by one time interval or pulse. The first / second entry for the $\Delta T$s gives $\rho$ when the $\Delta T$s are unnormalised / normalised by $T_{90}$. The first / second entry for the PAs gives $\rho$ when the PAs are unnormalised / normalised by the maximum peak in the burst.

| Total Number | $\rho$   | Probability |
|--------------|----------|-------------|
| 140          | 0.42/0.30| $1.7 \times 10^{-12}/3.0 \times 10^{-3}$ |
| 84           | 0.48/0.32| $4.9 \times 10^{-6}/3.2 \times 10^{-3}$ |
| 213/107      | 0.39/0.24| $5 \times 10^{-9}/1.1 \times 10^{-2}$ |
| 140/84       | 0.13/−0.09| 0.13/0.42  |
Fig. 3. The distributions of pulse area and amplitude selected at $\tau_\sigma \geq 5$ and $\tau_i \geq 50\%$ and consistent lognormals (dashed lines). These distributions were generated from 55 GRBs that were summed over two BATSE Large Area Detectors.

Fig. 4. The distribution of time intervals between the pulses, $\Delta T$, selected at $\tau_\sigma \geq 5$ and consistent lognormal (dashed line).

Mészáros, 1994). The internal shock model can account for the results obtained on long and short GRBs provided the cause of the pulses and the correlated values of $\Delta T$ can be attributed to the central engine. It has been shown that the time intervals between glitches in pulsars and outbursts in SGRs are lognormally distributed (Quilligan et al., 2001). The similar distributions of $\Delta T$ in short and long GRBs are indirect evidence for rotation powered systems with super-strong magnetic fields.

There is strong evidence that long GRBs originate in star forming galaxies providing evidence that they are linked to massive stars and supernovae (Mészáros, 2001). A variety of models, such as collapsars and hypernovae have been proposed as progenitors (e.g. MacFadyen & Woosley 1999). Models of these systems imply that jets can be generated to produce GRBs by an internal shock model. These models cannot account for GRBs with $T_{90}$ less than about 5s. The shorter GRBs have been attributed to neutron star (NS) - NS mergers or NS - black hole mergers (e.g. Ruffert & Janka 1999). A common ingredient of most GRB models is the formation of a black hole with a temporary torus that accretes and powers the relativistic jets and the GRBs. The overall energetics of the various progenitor models differ by at most an order of magnitude. The GRBs appear to have the same emission mechanism and possibly different progenitors for long and short bursts.

5. Conclusions

A sample of bright GRBs with $T_{90}<2\ s$ have been denoised and analysed by an automatic pulse selection algorithm. The results show that the distribution of the properties of isolated pulses and time intervals between all pulses are compatible with lognormal distributions. The same mechanism seems to be responsible for both long and short GRBs and is attributed to the internal shock model.

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