PROPERTIES OF GAMMA-RAY BURST TIME PROFILES USING PULSE DECOMPOSITION ANALYSIS

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ABSTRACT

The time profiles of many gamma-ray bursts consist of distinct pulses, which offers the possibility of characterizing the temporal structure of these bursts using a relatively small set of pulse shape parameters. This pulse decomposition analysis has previously been performed on a small sample of bright, long bursts using binned data from BATSE, which comes in several data types, and on a sample of short bursts using the BATSE time-tagged event (TTE) data type. We have developed an interactive pulse-fitting program using the phenomenological pulse model of Norris et al. and a maximum-likelihood fitting routine. We have used this program to analyze the time-to-spill (TTS) data for all bursts observed by BATSE up through trigger number 2000, in all energy channels for which TTS data is available. This represents a total of 211 distinct bursts analyzed in one or more energy channels. We present statistical information on the attributes of pulses comprising these bursts, including relations between pulse characteristics in different energy channels and the evolution of pulse characteristics through the course of a burst. We carry out simulations to determine the biases that our procedures may introduce. We find that pulses tend to have shorter rise times than decay times, and tend to be narrower and peak earlier at higher energies. We also find that pulse brightness, pulse width, and pulse hardness ratios do not evolve monotonically within bursts, but that the ratios of pulse rise times to decay times tend to decrease with time within bursts.

Subject headings: gamma rays: bursts — methods: data analysis

1. INTRODUCTION

There has been considerable recent progress in the study of gamma-ray bursts. Much of this results from the detection of bursts by BeppoSAX with good locations that have allowed the detection of counterparts at other wavelengths. This has allowed measurements of redshifts that have firmly established that these bursts are at cosmological distances. However, only a few redshifts are known, so there is still much work to be done in determining the mechanisms that produce gamma-ray bursts. Investigation of time profiles and spectra can shed new light on this subject.

The vast majority of gamma-ray bursts that have been observed have been observed only by BATSE. These data can be classified into three major types: burst locations with relatively large uncertainties, temporal characteristics, and spectral characteristics. Here we examine temporal characteristics of bursts, along with some spectral characteristics.

The temporal structure of gamma-ray bursts exhibit very diverse morphologies, from single simple spikes to extremely complex structures. So far, the only clear division of bursts based on temporal characteristics that has been found is the bimodal distribution of the $T_{90}$ and $T_{50}$ intervals, which are measures of burst durations (Kouveliotou et al. 1993; Meegan et al. 1996a). In order to characterize burst time profiles, it is useful to be able to describe them using a small number of parameters.

Many burst time profiles appear to be composed of a series of discrete, often overlapping pulses, often with a “fast rise, exponential decay” (FRED) shape (Norris et al. 1996). These pulses have durations ranging from a few milliseconds to several seconds. The different pulses might, for example, come from different spatial volumes in or near the burst source. Therefore, it may be useful to decompose burst time profiles in terms of individual pulses, each of which rises from background to a maximum and then decays back to background levels. Here we have analyzed gamma-ray burst time profiles by representing them in terms of a finite number of pulses, each of which is described by a small number of parameters. The BATSE data used for this purpose are described in § 2. The basic characteristics of the time profiles based on the above model are described in § 3, and some of the correlations between these characteristics are described in § 4. (Further analysis of these and other correlations and their significance are discussed in an accompanying paper, Lee, Bloom, & Petrosian 2000.) Finally, a brief discussion is presented in § 5.

2. THE BATSE TIME-TO-SPILL DATA

The BATSE time-to-spill (TTS) burst data type records the times required to accumulate a fixed number of counts, usually 64, in each of four energy channels (Meegan 1991). These time intervals give fixed multiples of the reciprocals of the average count rates during the spill intervals. There has been almost no analysis done using the TTS data, because they are less convenient to use with standard algorithms than the BATSE time-tagged event (TTE) data or the various forms of binned BATSE data. The TTS data use the limited memory on board the CGRO more efficiently than do the binned data types, because at lower count rates it stores spills less frequently, with each spill having the same constant fractional statistical error. On the other hand, the binned data types always store binned counts at the same intervals, so that at low count rates the binned counts have
a large fractional statistical error. The variable time resolution of the TTS data ranges from under 50 ms at low background rates to under 0.1 ms in the peaks of the brightest bursts. In contrast, the finest time resolution available for binned data is 16 ms for the medium energy resolution (MER) data, and then only for the first 33 s after the burst trigger. The TTS data can store up to 16,384 spill events (over $10^6$ counts) for each energy channel, and this is almost always sufficient to record the complete time profiles of bright, long bursts. This is unlike the TTE data, which are limited to 32,768 counts in all four energy channels combined. For short bursts, the TTE data have finer time resolution than the TTS data, because they record the arrival times of individual counts with 2 $\mu$s resolution. Furthermore, the TTE data also contain data from before the burst trigger time. One reason why this is useful is that some of the shortest bursts are nearly over by the time burst trigger conditions have been met, so the TTS and MER data are not very useful for these bursts.

Figure 1 shows a portion of the time profile of BATSE trigger number 1577 (GRB 4B 920502B) that contains a spike with duration shorter than 1 ms. The data with the finest time resolution, the TTE data, end long before the spike occurs, so the TTS data give the best representation of the spike. The binned data with the finest time resolution, the MER data with 16 ms bins, are unavailable for this burst, as are the PREB and DISCSC data with 64 ms bins.

For a Poisson process, the individual event times in the TTE data and the binned counts in the various binned data types follow the familiar exponential and the Poisson distributions, respectively. The spill times recorded in the TTS data follow the gamma distribution, which is the distribution of times needed to accumulate a fixed number of independent (Poisson) events occurring at a given rate. The probability of observing a spill time $t_s$ is

$$P(t_s) = \frac{t_s^{N-1} \Gamma(N)}{N^N},$$

where $N$ is the number of events per spill and $R$ is the rate of individual events. This probability distribution is closely related to the Poisson distribution, which gives the number of events occurring within fixed time intervals for the same process of independent individual events, such as photon arrivals.

2.1. The Pulse Model and the Pulse-Fitting Procedure

We now describe the pulse model used to fit GRB time profiles, and the pulse-fitting procedure. The pulse model we use is the phenomenological pulse model of Norris et al. (1996). In this model, each pulse is described by five parameters with the functional form

$$I(t) = A \exp \left( \frac{t - t_{max}}{\sigma_r d} \right),$$

where $t_{max}$ is the time at which the pulse attains its maximum, $\sigma_r$ and $\sigma_d$ are the rise and decay times, respectively, $A$ is the pulse amplitude, and $v$ (the "peakness") gives the sharpness or smoothness of the pulse at its peak. Pulses can, and frequently do, overlap. Stern, Poutanen, & Svensson (1997) have used the same functional form to fit averaged time profiles (ATPs) of entire bursts.

We have developed an interactive pulse-fitting program that can automatically find initial background level and pulse parameters using a Haar wavelet denoised time profile (Donoho 1992), and allows the user to add or delete pulses graphically. The program then finds the parameters of the pulses and a background with a constant slope by using a maximum-likelihood fit for the gamma distribution (eq. [1]) that the TTS spill times follow (Lee, Bloom, & Scargle 1996, 1998; Lee 2000).

The data that we use in this paper are the TTS data for all gamma-ray bursts in the BATSE 3B catalog (Meegan et al. 1996b) up to trigger number 2000, covering the period from 1991 April 21 through 1992 October 22, in all channels that are available and show time variation beyond the normal Poisson noise of the background. We fitted each channel of each burst separately and obtained 574 fits for 211 bursts, with a total of 2465 pulses. In many cases, the data for a burst showed no activity in a particular energy channel, only the normal background counts, so there were no pulses to fit. This occurred most frequently in energy channel 4. In other cases, the data for a burst contained telemetry gaps or were completely missing in one or more channels, making it impossible to fit those channels.

This procedure is likely to introduce selection biases, which can be quantified through simulation. To determine these biases, we simulated a set of bursts with varying numbers of pulses, with distributions of pulse and background parameters based on the observed distributions in actual bursts. We generated independent counts according to the simulated time profiles to create simulated TTS data, which we subjected to the same pulse-fitting procedure used for the actual BATSE data. The detailed results of this simulation are discussed in the Appendix. We contrast the results from the actual data with those from the simulations where necessary and relevant.

2.2. Count Rates and Time Resolution

The time resolution of the TTS data can be determined from the fitted background rates and the amplitudes of the individual pulses (discussed in § 3.3), at both the background levels and the peaks of the pulses. Table 1, columns (2)–(5) show the percentage of bursts in our fitted sample where the time resolution at background levels and at the peak of the highest amplitude pulse are finer than 64 and

![Figure 1](https://example.com/figure1.png)
16 ms, the time resolutions of the more commonly used DISCSC and MER data, respectively. The background rates are taken at the time of the burst trigger, and ignore the fitted constant slope of the background. The rates at the peaks of the highest amplitude pulses include the background rates at the peak times of the pulses calculated with the background slopes. However, these rates ignore overlapping pulses, so the actual time resolution will be finer, since the actual count rates will be higher. Note that even at background levels, the TTS data always have finer time resolution than the DISCSC data, except in energy channel 4, where the DISCSC data have finer time resolution for 32% of the bursts in our sample.

Table 1, columns (6)–(7) shows the percentage of individual pulses for which the TTS data have time resolution finer than 16 and 64 ms, respectively, at the pulse peaks. Again, the count rates include the fitted background rates at the peak times of the pulses, but ignore overlapping pulses. For all individual pulses, the TTS data have finer time resolution at their peaks than the DISCSC data.

3. GENERAL CHARACTERISTICS OF PULSES IN BURSTS

In this section we describe characteristics of pulses in individual bursts and in the sample as a whole.

3.1. Numbers of Pulses

The number of pulses in a fit range from 1 to 43, with a median of 2 pulses per fit in energy channels 1, 2, and 4, and a median of 3 pulses per fit in energy channel 3 (see Fig. 2). The numbers of pulses per fit follows the trend of pulse amplitudes, which tend to be highest in energy channel 3, followed in order by channels 2, 1, and 4, respectively. This appears to occur because higher amplitude pulses are easier
to identify above the background, and is consistent with the simulation results shown in the Appendix.

Norris et al. (1996) have used the pulse model of equation (2) to fit the time profiles of 45 bright, long bursts. They analyzed the BATSE PREB and DISCSC data types, which contain four-channel discriminator data with 64 ms resolution beginning 2 s before the burst trigger. For their selected sample of bursts, they fitted an average of 10 pulses per burst, with no time profiles consisting of only a single pulse. This number is considerably higher than the mean number of pulses per fit for our sample of bursts, probably because their sample was selected for high peak flux and long duration, which makes it easier to resolve more pulses.

3.2. Matching Pulses between Energy Channels

To see how attributes of pulses within a burst vary with energy, it is necessary to match pulses in different energy channels. Although burst time profiles generally have similar features in different energy channels, this matching is not straightforward, since the number of pulses fitted to a burst time profile very often differs between energy channels. We have used a simple automatic algorithm for matching pulses between adjacent energy channels. This algorithm begins by taking all pulses from the channel with fewer pulses. It then takes the same number of pulses of highest amplitude from the other channel, and matches them in time order with the pulses from the channel with fewer pulses. For example, the time profiles of BATSE trigger number 1577 were fitted with nine pulses in energy channel 3, and only four pulses in channel 4. This algorithm simply matches all four pulses in channel 4 in time order with the four highest amplitude pulses in channel 3. While this method will not always correctly match individual pulses between energy channels and will result in broad statistical distributions, it should still preserve central tendencies and yield useful statistical information.

3.3. Brightness Measures of Pulses: Amplitudes and Count Fluences

The amplitude of a pulse, parameter $A$ in equation (2), is the maximum count rate within the pulse, and measures the observed intensity of the pulse, which depends on the absolute intensity of the pulse at the burst source and the distance to the burst source. The amplitudes of the fitted pulses ranged from 40 counts s$^{-1}$ to over 500,000 counts s$^{-1}$ (see Table 2 and Fig. 3). Pulses tend to have the highest amplitudes in energy channel 3, followed in order by channels 2, 1, and 4, in agreement with Norris et al. (1996). The central 68% of the pulse amplitude distributions span a range of about 1 order of magnitude in each of the four energy chan-

| ENERGY CHANNEL (keV) | Minimum (counts s$^{-1}$) | Median (counts s$^{-1}$) | Maximum (counts s$^{-1}$) | RATIO 84%/16% |
|----------------------|---------------------------|--------------------------|---------------------------|----------------|
| 1                    | 47                        | 2200                     | 136,000                   | 10.8           |
| 2                    | 85                        | 2700                     | 543,000                   | 12.9           |
| 3                    | 93                        | 3000                     | 250,000                   | 16.2           |
| 4                    | 43                        | 1900                     | 63,000                    | 11.8           |

Fig. 3.—Distribution of pulse amplitudes for all pulses from all bursts, by energy channel. Note that the rapid decline at low amplitudes is partly due to the BATSE triggering procedure and partly due to the fitting procedure. See Fig. 14.
nels, with a somewhat greater range in channel 3. We show in the Appendix that the fitting procedure tends to miss pulses with low amplitudes, so that the distributions shown may be strongly affected by selection effects in the fitting procedure.

The amplitude of the highest amplitude pulse in a burst is an approximation to the instantaneous peak flux above background of that burst in that energy channel. The peak flux is often used as an indicator of the distance to the burst source. Since pulses can overlap, the highest pulse amplitude can be less than the actual background-subtracted peak flux. The BATSE burst catalogs give background-subtracted peak fluxes for 64, 256, and 1024 ms time bins in units of photons cm$^{-2}$ s$^{-1}$, for which effects such as the energy acceptances of the detectors and the orientation of the spacecraft, and hence the detectors relative to the source, have been accounted for and removed. The BATSE burst catalog also lists raw peak count rates that are not background-subtracted or corrected for any of the effects described, averaged over 64, 256, and 1024 ms time bins in the second most brightly illuminated detector for each burst. These peak count rates are primarily useful for comparison with the BATSE event trigger criteria. In some bursts, the highest pulses are considerably narrower than the shortest time bins used to measure peak flux in the BATSE burst catalog. For these bursts, these peak fluxes will be lower than the true peak flux, and the fitted pulse amplitudes are likely to be a better measure of the true peak flux. The distributions of the highest pulse amplitudes are shown in Table 3 and Figure 4. Since BATSE selectively

| Energy Channel | Minimum (counts s$^{-1}$) | Median (counts s$^{-1}$) | Maximum (counts s$^{-1}$) | Ratio 84%/16% |
|----------------|---------------------------|--------------------------|---------------------------|---------------|
| 1              | 241                       | 2200                     | 136,000                   | 11.1          |
| 2              | 148                       | 2800                     | 543,000                   | 9.9           |
| 3              | 116                       | 3500                     | 250,000                   | 12.4          |
| 4              | 82                        | 1500                     | 63,000                    | 18.8          |

Table 3: Characteristics of Distribution of Pulse Amplitudes for Highest Amplitude Pulse in Each Burst

triggers on events with high peak flux, the distributions must be strongly affected by the trigger criteria.

Figure 5 shows the number of pulses in each fit plotted against the amplitudes of all the pulses comprising each fit. It shows that in fits with more pulses, the minimum pulse amplitude, which can be seen from the left boundary of the distribution, tends to be higher. This could result in part from intrinsic properties of the burst sources, but may also result at least in part from a selection effect: in a complex time profile with many overlapping pulses, low-amplitude pulses, which have poor signal-to-noise ratios, will be more difficult to resolve, while in a less complex time profile, they will be easier to resolve. This hypothesis appears to be confirmed by the simulation results shown in the Appendix. Table 4, columns (2)–(3) give the Spearman rank-order correlation coefficients, commonly denoted as $r_s$, for the

Fig. 4.—Distribution of pulse amplitudes, highest amplitude pulse in each burst, by energy channel. Dashed lines show bursts containing only a single pulse. The more rapid decline at low amplitudes as compared with that in Fig. 3 is due to the stronger influence of the BATSE triggering procedure. The fitting procedure has a weaker influence here.
Fig. 5.—Number of pulses per burst vs. pulse amplitudes of all pulses, by energy channel. Compare with Fig. 15 for simulated data. Note that there exists a positive correlation between the two quantities.

A joint distribution of pulse amplitudes and numbers of pulses in the corresponding bursts shown in Figure 5, as well as the probability that a random data set of the same size with no correlation between the two variables would produce the observed value of $r_S$. It shows strong positive correlations between pulse amplitudes and the number of pulses in the fit for all energy channels. These correlations appear to be stronger than those arising in the fits to simulations shown below in Table 16, columns (2)–(3).

The area under the light curve of a pulse gives the total number of counts contained in the pulse, which is its count fluence. It is given in terms of the pulse parameters and the gamma function by

$$ \mathcal{F} = A \int_{-\infty}^{\infty} I(t) \, dt = A \frac{\sigma_p + \sigma_d}{\nu} \Gamma\left(\frac{1}{\nu}\right). \quad (3) $$

The count fluence is a measure of the observed integrated luminosity of the pulse, which depends on the total number of photons emitted by the source within the pulse and the distance to the burst source. We show in the Appendix that the fitting procedure tends to miss pulses with low count fluences.

Figure 6 shows the number of pulses in each fit versus the count fluences of the individual pulses. It shows that in bursts containing more pulses, the individual pulses tend to contain fewer counts. We shall see in the next section that pulses tend to be narrower in more complex bursts. This result for count fluences implies that the tendency for pulses to be narrower is stronger than the tendency for pulses to have higher amplitudes in more complex bursts. Table 4, columns (4)–(5) shows that the corresponding negative correlations between pulse count fluences and numbers of pulses per fit are statistically significant in energy channels 1 and 2, but not in channels 3 and 4. The fits to simulations (see below, Fig. 17 and Table 16, cols. [4] and [5]) do not show the same tendency, so this most likely is not caused by selection effects in the pulse-fitting procedure.

| Table 4 | Correlation between Number of Pulses per Burst and Amplitudes, Count Fluences, and Widths of All Pulses |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Energy Channel | Amplitude | Count Fluence | Width |
| (1)             | (2)         | (3)            | (4)            | (5)            | (6)            | (7)            |
| 1               | 0.37        | $3.9 \times 10^{-18}$ | -0.17 | $9.2 \times 10^{-5}$ | -0.36 | $1.8 \times 10^{-17}$ |
| 2               | 0.36        | $1.8 \times 10^{-24}$ | -0.20 | $3.4 \times 10^{-8}$ | -0.35 | $8.0 \times 10^{-24}$ |
| 3               | 0.30        | $4.2 \times 10^{-20}$ | -0.04 | 0.21             | -0.23 | $9.4 \times 10^{-12}$ |
| 4               | 0.45        | $2.2 \times 10^{-15}$ | -0.13 | 0.027            | -0.28 | $1.3 \times 10^{-5}$  |
3.4. Pulse Widths and Time Delays

Timescales in gamma-ray bursts are likely to be characteristic of the physical processes that produce them. However, since some, and possibly all, bursts are produced at cosmological distances, all observed timescales will be affected by cosmological time dilation, and will not represent the physical timescales at the sources.

3.4.1. Pulse Widths

The most obvious timescale that appears in the pulse decomposition of gamma-ray burst time profiles is the pulse width, or duration. We measure the duration, or width, of a pulse using its full-width at half-maximum (FWHM), which is given by

$$T_{\text{FWHM}} = (\sigma_p + \sigma_d)(\ln 2)^{1/\nu}.$$  \hspace{1cm} (4)

The distributions of the pulse widths, which are shown in Figure 7 and columns (2)–(3) of Table 5, peak near 1 s in all energy channels, with no sign of the bimodality seen in total burst durations mentioned above. Pulses tend to be narrower (shorter) at higher energies.

The narrowing of pulses in higher energy channels can also be measured from the ratios of pulse widths of matched pulses in adjacent energy channels, as shown in Table 6. We can test the hypothesis that pulses tend to be narrower at higher energies by computing the probability that the observed numbers of pulse width ratios less than 1 will occur by chance if pulse width ratios less than 1 and greater than 1 are equally probable. This probability can be computed from the binomial distribution, and is shown in the last column of Table 6. The table shows less narrowing than a simple comparison of median pulse widths from Table 5 would suggest, although it also shows that the hypothesis that pulses do not become narrower at higher energies is strongly excluded between channels 1 and 2 and between channels 2 and 3. Qualitatively similar kinds of trends have been shown to be present in individual pulses (Norris et al. 1996) and composite pulse shapes of many bursts (Link, Epstein, & Priedhorsky 1993; Fenimore & Bloom 1995).

There are, however, some quantitative differences. For example, we find that there seems to be less narrowing at higher energies; the pulse-width ratios tend to be closer to 1 between energy channels 3 and 4 than for the lower energy channels (although the statistics are poorer, as with anything involving channel 4), which is the opposite of the tendency found by Norris et al. (1996). We can use the Kolmogorov-Smirnov test to determine if the distributions

| ENERGY CHANNEL | FWHM Median (s) | Ratio 84%/16% | Peakedness v Median | Ratio 84%/16% |
|----------------|-----------------|---------------|---------------------|---------------|
| 1              | 1.86            | 19.9          | 1.22                | 5.3           |
| 2              | 1.05            | 23.0          | 1.26                | 5.6           |
| 3              | 0.68            | 22.9          | 1.26                | 5.7           |
| 4              | 0.41            | 21.4          | 1.17                | 5.8           |
| All            | 0.90            | 27.0          | 1.25                | 5.6           |
3.4.2. Pulse Widths and Numbers of Pulses

Figure 8 and Table 4, columns (6)–(7) shows the relation between the number of pulses per burst and the widths of the pulses. These show that pulses tend to be narrower in bursts with more pulses. This may be an intrinsic property of GRBs, or it may be a selection effect arising because narrower pulses have less overlap with adjacent pulses, hence making them easier to resolve, so more pulses tend to be identified in bursts with narrower pulses. This may also be a side effect of correlations between other burst and pulse characteristics with the number of pulses per burst and the pulse widths. Table 4 shows strong negative correlations between the numbers of pulses per fit and the pulse widths. The fits to simulations shown below in Figure 19 and Table 16, columns (6)–(7), do not have the same tendency. This suggests that the negative correlation between the number of pulses in each fit and the pulse widths seen in the fits to actual bursts do not result from selection effects in the pulse-fitting procedure, but are intrinsic to the burst production mechanism, or may arise from other effects.

3.4.3. Time Delays between Energy Channels

Table 7, columns (2)–(3) show the differences, or time delays, between the peak times, $t_{\text{max}}$, of all pulses matched between adjacent energy channels. It shows a significant tendency for individual pulses to peak earlier at higher energies. This has been previously observed, and described as a hard-to-soft spectral evolution of the individual pulses (Norris et al. 1986, 1996). The time delays found here are greater than those found by Norris et al. (1996), who found an average pulse peak time delay between adjacent energy

### Table 6

| Energy Channels | Median Width Ratio | < 1 | Binomial Probability | K-S Probability |
|-----------------|--------------------|-----|----------------------|-----------------|
| 2/1             | 0.73               | 304/446 (68%) | $1.7 \times 10^{-14}$ | $1.1 \times 10^{-5}$ |
| 3/2             | 0.68               | 436/625 (70%) | $< 10^{-16}$ | $8.7 \times 10^{-7}$ |
| 4/3             | 0.83               | 153/258 (59%) | 0.0028 | 0.62 |
channels of \( \sim 20 \) ms. Comparing the peak times of the highest amplitude pulses in each fit between adjacent energy channels also shows a significant tendency for bursts to peak earlier at higher energies (see Table 7, cols. [5]–[7]). The time delays between energy channels observed here and elsewhere are likely to result from intrinsic properties of the burst sources.

### 3.5. Pulse Shapes: Asymmetries and the Peakedness, \( \nu \)

Although the pulse model uses separate rise and decay times as its basic parameters, it is often more natural to consider the widths and asymmetries of pulses, which give equivalent information to the rise and decay times. The ratios of pulse rise times to decay times, \( \sigma_r/\sigma_d \), are a convenient way to measure the asymmetry of pulses, and depend only on the shapes of pulses. The asymmetry ratios cover a very wide range of values, but there is a clear tendency for pulses to have shorter rise times than decay times (see Fig. 9).

Table 8 shows that the hypothesis that pulses are symmetric is strongly excluded, especially in energy channels 2 and 3. The binomial probability is not computed for all pulses in all energy channels combined, because pulses cannot be considered to be independent between energy channels. From columns (2) and (3), it can also be seen that the degree of the asymmetry is not significantly different for the different energy channels. Norris et al. (1996) found average values of \( \sigma_d/\sigma_r \) (the inverse of the ratio used here) ranging from 2 to 3 for pulses in their selected sample of bursts, and with about 90% of pulses having shorter rise times than decay times.

Several other studies, including Nemiroff et al. (1994) and Romero (1999), have examined the asymmetry of the entire time profiles of bursts, using a variety of statistics, and have generally found that most bursts tend to have shorter rise times than decay times, in general agreement with the result found here and by Norris et al. (1996) that individual pulses tend to have shorter rise times than decay times. However,

**TABLE 7**

**Characteristics of Distribution of Time Delays between Adjacent Energy Channels**

| ENERGY CHANNELS | ALL MATCHED PULSES | HIGHEST AMPLITUDE PULSE |
|----------------|--------------------|-------------------------|
|                | Median Lag (s)     | >0 (3) | Binomial Probability (4) | Median Lag (s) | >0 (6) | Binomial Probability (7) |
| (1)            | (2)                | (3)    |                        | (5)            | (6)    |                        |
| 1-2 \( \ldots \) | 0.11              | 290/446 (65%) | 2.2 \( \times 10^{-10} \) | 0.08          | 95/141 (67%) | 3.7 \( \times 10^{-5} \) |
| 2-3 \( \ldots \) | 0.27              | 459/625 (73%) | \(< 10^{-10} \)           | 0.05          | 97/151 (64%) | 0.000047                |
| 3-4 \( \ldots \) | 0.01              | 140/258 (54%) | 0.17                     | 0.14          | 47/67 (70%) | 0.000097                |
Fig. 9.—Distribution of pulse asymmetry ratios for all pulses from all bursts, by energy channel. See analysis in Table 8.

Fig. 10.—Distribution of the peakedness parameter $\nu$ for all pulses from all bursts, by energy channel. See analysis in Table 5, cols. (4)-(5).
there are some bursts for which the entire burst and its constituent pulses have opposite asymmetries (Romero 1999). The two kinds of results, for entire bursts and for individual pulses, can be directly compared for simple bursts consisting of a single pulse. Romero (1999) found that 4% of a sample of 631 bursts were single-peaked and had longer rise times than decay times using all of their asymmetry measures. Our sample of single-pulse bursts shows a much broader range of asymmetry ratios $\sigma_r/\sigma_d$ than do the pulses in all bursts, and there appears to be a statistically insignificant tendency for single-pulse bursts to be asymmetric (probability 0.21 for the asymmetry to occur by chance in channel 1, higher in other channels). This may simply arise from the small number (only 70 in channel 2, fewer in other channels; see also Fig. 2) of single-pulse bursts in our sample (Lee 2000). It is important to have better data and a clearer resolution of these differences, because pulses with $\sigma_r/\sigma_d > 1$ will be difficult to explain in the internal shock scenario.

The relation of the peakedness parameter $v$ to physical characteristics of gamma-ray burst sources is far less clear than for other pulse attributes. Nevertheless, it does give information that can be used to compare the shapes of different pulses. The peakedness $v$ has a median value near 1.2 in all energy channels, so that pulses tend to have shapes between an exponential, for which $v = 1$, and a Gaussian, for which $v = 2$ (see Fig. 2 and Table 5, cols. [4]-[5]). Stern et al. (1997) use the functional form of equation (2) to fit averaged time profiles of many bursts rather than individual constituent pulses, and find that $v \approx 1/3$ for the averaged time profiles.

4. CORRELATIONS BETWEEN PULSE CHARACTERISTICS

Correlations between different characteristics of pulses, or the lack thereof, may reveal much about gamma-ray bursts that the distributions of the individual characteristics cannot. Some correlations may arise from intrinsic properties of the burst sources, while others may result from the differing distances to the sources. The first kind of correlation may be present among pulses of individual bursts or among the whole population of bursts, while the second kind will not be present among pulses of individual bursts. In order to distinguish between these two kinds of effects, it is useful to examine correlations of pulse characteristics both between different bursts and between pulses within individual bursts.

It is simplest to find correlations between characteristics of all pulses, but such correlations would combine both kinds of effects, and the statistics would be weighted in favor of bursts containing more pulses. It is also possible to select a single pulse from each burst, and find correlations between the characteristics of these pulses from burst to burst in order to look for effects arising from the distances to burst sources. However, if the correlations are taken using the single highest amplitude or highest fluence pulse from each burst, then they could still be affected by correlations of pulse characteristics within individual bursts. For example, consider a situation in which amplitudes and durations of pulses within individual bursts are correlated, and in which pulse amplitudes and durations follow a common distribution for all bursts. In such a case, if we select the single highest amplitude pulse from each burst, we would find a spurious correlation between highest pulse amplitude and duration between different bursts.

Correlation results that compare and contrast the cosmological and intrinsic effects will be discussed in greater detail in the accompanying paper, Lee et al. (2000). Here we describe our method and some other correlation results.

One way to find correlations of pulse characteristics within individual bursts is to calculate a correlation coefficient for each burst and examine the distribution of the degrees of correlation, for example to see if the correlation coefficients were positive for a large majority of bursts. The Spearman rank-order correlation coefficient is used for this purpose here. When using the Spearman rank-order correlation coefficient, the coefficients for the individual bursts are often not statistically significant, because the number of pulses in each burst is not large, even though the coefficients for the different bursts may be mostly positive or mostly negative. We can test the hypothesis that there is no correlation, because in the absence of any correlation we would expect an equal number of bursts with positive and negative correlations, so the probability that the observed numbers of bursts with positive and negative correlations could occur by chance if there were no correlation is given by the binomial distribution. This is the method used here. This method ignores the strengths of the individual correlations, so it is more sensitive to a weak correlation that affects large numbers of bursts than it is to a strong correlation that affects only a small number of bursts.

4.1. Spectral Characteristics

The data that we use have only very limited spectral information: only four energy channels. We can investigate spectral characteristics by using the “hardness ratios” of individual pulses. The hardness ratio of a pulse between two specified energy channels is the ratio of the fluxes or fluences of the pulse between the two energy channels. Although the actual numerical values of the hardness ratios depend on the somewhat arbitrary boundaries of the energy channels, the values can be compared between different pulses, and between different bursts.

There have been several claims of correlations between peak or average hardness ratios and durations among bursts, with shorter bursts being harder (Kouveliotou et al. 1993, 1996), and there has been some analysis of the cosmological significance of this. Here we investigate similar correlations for bursts, and for pulses in individual bursts.

4.1.1. Pulse Widths

Table 9, columns (2)-(3) shows the correlations between the pulse amplitude hardness ratios and the pulse widths for the highest amplitude pulse in each burst. The pulse widths used are arithmetic means of the widths in the two adjacent energy channels that the hardness ratios are taken between,
e.g., hardness ratios between channels 2 and 3 are compared with pulse widths averaged over channels 2 and 3. In all pairs of adjacent energy channels, the highest amplitude pulse has a slight tendency to be narrower when the burst is harder, as measured using peak flux, but this does not appear to be statistically significant, except possibly between channels 3 and 4. This may be a signature of weak redshift effects, whereby the higher the redshift, the softer the spectrum and the longer the duration.

Table 10, columns (4)–(5) shows the correlations between pulse amplitude hardness ratios and pulse amplitudes within bursts. As evident, there is almost equal probability for positive and negative correlations. We conclude, therefore, that there is no significant tendency for longer or shorter duration pulses to have harder or softer spectra, measured using peak flux.

### 4.1.3. Pulse Amplitudes

Table 9, columns (6)–(7) shows the correlations between the pulse amplitude hardness ratio and the pulse amplitudes for the highest amplitude pulse in each burst. If the peak luminosity of the highest amplitude pulse is a standard candle or has a narrow distribution, the effects of cosmological redshift would introduce a correlation between hardness ratio and amplitude. In all pairs of adjacent energy channels, the highest amplitude pulse has a slight tendency to be stronger when the burst is harder, as measured using peak flux, but this is not statistically significant (except possibly between channels 2 and 3), indicating that the distribution of the above-mentioned luminosity is broad.

Table 10, columns (4)–(5) shows the correlations between pulse amplitude hardness ratios and pulse amplitudes within bursts. The pulse amplitudes are summed over the two adjacent energy channels that the hardness ratios are taken between. There appears to be no statistically significant tendency for higher amplitude pulses to have harder or softer spectra, although slightly more bursts show a positive correlation (higher amplitude pulses are harder) than a negative correlation (higher amplitude pulses are softer.) This points to a weak or negligible intrinsic correlation between these quantities.

### 4.1.4. Count Fluence Hardness Ratios

In the following discussion, we carry out the same tests using the hardness ratio measured by count fluence instead of amplitude, for bursts and pulses within bursts.

Table 11, columns (2)–(3) shows the correlations between the total burst count fluence hardness ratios and the pulse widths for the highest amplitude pulses of the bursts. A positive correlation (harder bursts having shorter durations) would be expected if the pulse total energy had a narrow intrinsic distribution. There is no consistent or statistically significant tendency for the highest amplitude pulse in each burst to be wider or narrower when the burst is harder or softer, as measured using fluence.

Table 12, columns (2)–(3) shows the correlations between pulse count fluence hardness ratios and pulse widths within bursts. In channels 1 and 2, more bursts show negative correlations between the two quantities, i.e., longer duration pulses tend to have softer spectra, as measured using count fluence, and this effect, which may be statistically significant, indicates the presence of an intrinsic correlation. There are no statistically significant effects between channels 2 and 3 or between channels 3 and 4.

Table 11, columns (4)–(5) shows the correlations between the total burst count fluence hardness ratios and the intervals between the two highest amplitude pulse in each fit. In all pairs of adjacent energy channels, the two highest amplitude pulses have a slight tendency to be closer together when the burst is harder (as expected from cosmological effects), but this is not statistically significant.

Table 11, columns (6)–(7) shows the correlations between the total burst count fluence hardness ratios and the total burst count fluence in each fit. There is no consistent or statistically significant tendency for harder or softer bursts to contain fewer or more counts.

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**TABLE 9**

| Energy Channels | Width | Interval | Amplitude |
|-----------------|-------|----------|-----------|
|                 | \( r_s \) | Probability | \( r_s \) | Probability | \( r_s \) | Probability |
| 2/1 ....... | -0.11 | 0.18 | -0.26 | 0.019 | 0.01 | 0.89 |
| 3/2 ....... | -0.21 | 0.010 | -0.06 | 0.57 | 0.28 | 0.00059 |
| 4/3 ....... | -0.41 | 0.00061 | -0.17 | 0.34 | 0.31 | 0.012 |

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**TABLE 10**

| Energy Channels | Width | Amplitude |
|-----------------|-------|-----------|
|                 | Positive Correlation | Binomial Probability | Positive Correlation | Binomial Probability |
|                 | (2) | (3) | (4) | (5) |
| 2/1 ....... | 45/83 (54%) | 0.44 | 44.5/83 (54%) | 0.51 |
| 3/2 ....... | 50/95 (53%) | 0.61 | 49/95 (52%) | 0.76 |
| 4/3 ....... | 14/33 (42%) | 0.38 | 20.5/33 (62%) | 0.16 |
| All ....... | 109/211 (52%) | ... | 114/211 (54%) | ... |
Table 12, columns (4)–(5) shows the correlations between pulse count fluence hardness ratios and pulse count fluences within bursts. The pulse count fluences are summed over the two adjacent energy channels that the hardness ratios are taken between. In channels 1 and 2, more bursts show negative correlations, i.e., higher fluence pulses tend to have softer spectra, but again, this intrinsic effect appears weak, and there is no significant effect in the other pairs of energy channels.

In summary, there seems to be little intrinsic correlation between the spectra, as measured by hardness ratio, and other pulse characteristics between bursts and among pulses. There may be weak (statistically not very significant) evidence for trends expected from cosmological redshift effects.

4.2. Time Evolution of Pulse Characteristics within Bursts

One class of correlations between pulse characteristics within bursts are those between the pulse peak time and other pulse characteristics. These indicate whether certain pulse characteristics tend to evolve in a particular way during the course of a burst. Again, we have used the method described in the previous section, calculating the Spearman rank-order correlation coefficients for the individual bursts and testing the observed numbers of bursts within bursts with positive and negative correlations using the binomial distribution.

4.2.1. Pulse Asymmetry Ratios

Table 13, columns (2)–(3) shows the number and fraction of bursts (in each channel) for which there is a negative correlation between the pulse asymmetry ratio \( \sigma_p/\sigma_d \) and peak time, i.e., for which the pulse asymmetry decreases with time. Fits for which the calculated Spearman rank-order correlation coefficient was 0, indicating no correlation, were counted as half for decreasing and half for increasing in order to calculate, using the binomial distribution, the probability of this occurring randomly if pulse amplitudes within bursts are equally likely to increase as to decrease with time. The probability was not calculated for all energy channels combined, because fits to the same burst in different energy channels cannot be considered independent, so the binomial distribution cannot be used.

Pulse asymmetry ratios more often decrease than increase with time during bursts, except in energy channel 4, which has the fewest pulses. This effect appears to be statistically significant in channel 3, and possibly channels 1 and 2. The fits to simulations (see below, Table 17) show no tendency for pulse asymmetries to increase or decrease within bursts. This indicates that the observed tendency for pulse asymmetry ratios to decrease with time within actual bursts does not arise from selection effects in the pulse-fitting procedure, so that any tendency would be intrinsic to gamma-ray bursts.

4.2.2. Pulse Rise and Decay Times and Pulse Widths

When we examine the evolution of the rise and decay times separately, instead of their ratios, and trace the evolution of the pulse widths, we find that there is a nearly equal and opposite trend of decreasing rise times, \( \sigma_r \), and increasing decay times, \( \sigma_d \), as the burst progresses. This gives rise to the evolution of the pulse asymmetry ratios described above, although the statistical significance of the evolution of rise times and decay times is weaker than for the pulse asymmetry ratios. The decrease in rise times is possibly a slightly stronger effect than the increase in decay times. However, the combined effect of these two trends is that there appears to be no statistically significant evolution of pulse widths (see Table 13, cols. [4]–[5]). This is in agreement with the results of Ramirez-Ruiz & Fenimore (1999, 2000), who found no evidence that pulse widths increase or decrease with time when fitting a power-law time dependence, using a small sample of complex bursts selected from the bright, long bursts fitted by Norris et al. (1996).

### Table 11

| Energy Channels | Width | Interval | Count Fluence |
|----------------|-------|----------|---------------|
| (1)            |       | (2)      | (3)           | (4)      | (5) |
| 2/1            | 0.02  | 0.84     | -0.10         | 0.36     | -0.01 |
| 3/2            | -0.22 | 0.0078   | -0.07         | 0.52     | 0.00 |
| 4/3            | 0.10  | 0.42     | -0.23         | 0.19     | 0.21 |

### Table 12

| Energy Channels | Width | Count Fluence |
|----------------|-------|---------------|
| (1)            |       |               |
| 2/1            | 52.5/83 (63%) | 51.5/83 (62%) |
| 3/2            | 47.5/95 (50%) | 47/95 (49%) |
| 4/3            | 18.5/33 (56%) | 20/33 (66%) |
| All            | 118.5/211 (56%) | 118.5/211 (56%) |
peak times of pulses in bursts and any other pulse characteristics except possibly the pulse asymmetry ratio, so that the pulses appear to result from random and independent emission episodes.

5. DISCUSSION

Decomposing burst time profiles into a superposition of discrete pulses gives a compact representation that appears to contain their important features, so this seems to be a useful approach for analyzing their characteristics. Our pulse decomposition analysis confirms a number of previously reported properties of gamma-ray burst time profiles using a larger sample of bursts with generally finer time resolution than in prior studies. These properties include tendencies for the individual pulses comprising bursts to have shorter rise times than decay times; for the pulses to have shorter durations at higher energies; and for the pulses to peak earlier at higher energies, which is sometimes described as a hard-to-soft spectral evolution of individual pulses.

Pulse rise times tend to decrease during the course of a burst, while pulse decay times tend to increase. When examining pulse widths, or durations, these two effects nearly balance each other; the apparent tendency for pulse widths to decrease during the course of a burst appears to be statistically insignificant. The ratios of pulse rise times to decay times tend to decrease during the course of a burst. The evolution of pulse asymmetry ratios does not arise from selection effects in the pulse-fitting procedure, so it is most likely intrinsic to the bursters.

No other pulse characteristics show any time evolution within bursts, although it is possible that there is non-monotonic evolution; for example, a pulse characteristic may tend to be greater at the beginning and end of a burst and smaller in the middle, and the tests used here would not be sensitive to this. In particular, it does not appear that either pulse amplitudes or pulse count fluences have any tendency to increase or decrease during the course of a burst. In addition, later pulses in a burst do not tend to be spectrally harder or softer than earlier pulses, although there is spectral softening within most pulses. The spectra of pulses within a burst also do not appear to be harder or softer for stronger or weaker pulses, or for longer or shorter duration pulses.

One may therefore conclude that the pulses in a burst arise from random and independent emission episodes such as those expected in the internal episodic shock model rather than the external shock models in which the presence of distinguishable pulses must be attributed to inhomoge-

\[ \frac{a_r}{a_4} \]
neities in the interaction of the blast-wave shock and the clumpy interstellar medium.

When examining similar correlations between the attributes of some characteristic pulses from burst to burst, we find some weak and tantalizing evidence that may be due to cosmological redshift effects. In the accompanying paper (Lee et al. 2000) we describe the correlation studies which can distinguish between trends due to cosmological redshifts and intrinsic trends.

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APPENDIX

TESTING FOR SELECTION EFFECTS

There are a number of ways in which the pulse-fitting procedure may introduce selection effects into correlations between pulse characteristics. One is that the errors in the different fitted pulse parameters may be correlated. Another is that the pulse-fitting procedure may miss some pulses by not identifying them above the background noise. Still another cause of selection effects is that overlapping pulses may be identified as a single broader pulse.

In order to determine the degree of importance of these selection effects, we have generated a sample of artificial burst time profiles using the pulse model with randomly generated but known pulse parameters, fitted the simulated bursts using the same procedure used for actual burst data, and compared the simulated and fitted pulse characteristics (Lee 2000).

A1. NUMBERS OF BURSTS AND PULSES

A total of 286 bursts were generated, with only one energy channel for each burst. For many of these, the limit of $2 \times 10^2$ counts was reached before the 240 s limit, which almost never occurred in the actual BATSE TTS data. These simulated bursts contained a total of 2671 pulses that had peak times before the limits of $2 \times 10^2$ counts and 240 s, while the fits to the simulated bursts contained a total of only 1029 pulses. Of these, 223 of the simulated bursts and 198 of the fits to the simulations contained more than one pulse (see Fig. 11 and Table 15). Note that in the fits to actual BATSE data, the largest number of fits containing more than one pulse was 116 for energy channel 3, so that the simulated data set is larger. Figure 12 shows the number of pulses fitted versus the number of pulses originally generated for each simulated bursts. It shows that the greatest

![Graph showing distribution of number of pulses](image-url)

**Fig. 11.**—Distribution of number of pulses in initial simulations (solid histogram) and in the results of the fits to the simulated data (dashed histogram).

**TABLE 15**

**Characteristics of Distribution of Number of Pulses in Simulations**

| Number of Pulses | Value for: | Median | Mean | Maximum | Single Pulse |
|------------------|------------|--------|------|---------|--------------|
|                  | (1)        | (2)    | (3)  | (4)     | (5)          |
| Simulation       | 3          | 9.3    | 126  | 62/286 (22%) |
| Fit to Simulation| 2          | 3.6    | 19   | 88/286 (31%) |
Fig. 12.—Number of pulses obtained from fits to the simulations vs. number in the initial simulations. Note that the selection effect of the fitting procedure is more pronounced in bursts with larger numbers of pulses.

Fig. 13.—Left: Distribution of differences between numbers of pulses from initial simulated bursts to fits to simulated bursts. A small number of bursts have many fewer pulses in the fits to simulations than in the initial simulations. Right: Distribution of ratios of numbers of pulses from initial simulated bursts to fits to simulated bursts.

differences between the fitted and the simulated number of pulses tends to occur in the most complex bursts. Figure 13 compares the numbers of pulses per fit between the simulations and the fits to simulations. Most (54%) of the fits to simulated bursts contain fewer pulses than the initial simulations, and for nearly all of the remaining simulated bursts, the number of pulses are the same for the initial simulations and the fits to simulations. The fits to simulations have a mean of 15 fewer pulses than the initial simulations, and a median of 1 fewer pulse. The fits to simulations have a geometric mean of 0.63 times as many pulses as the initial simulations, and a mean of 0.80 times as many pulses.

A2. BRIGHTNESS MEASURES OF SIMULATED PULSES

Figure 14 shows the distribution of pulse amplitudes in the original simulations and in the fits to simulations. It shows that the fitting procedure has a strong tendency to miss low-amplitude pulses. However, if we compare this with Figure 3, we see

Fig. 14.—Distribution of pulse amplitudes for all pulses from all bursts in initial simulations (solid histogram) and in the results of the fits to the simulated data (dashed histogram).
that in the fits to actual BATSE bursts, the fitting procedure found pulses with considerably lower amplitudes than it found in the fits to simulated bursts.

Figure 15 shows the number of pulses in each burst plotted against the amplitudes of all of the pulses comprising each fit. In the simulations, there are no correlations between pulse amplitudes and the number of pulses in the time profile, because the pulse amplitudes were generated independently of the number of pulses in each burst. In the fits to the simulations, pulse amplitudes tend to be higher in bursts containing more pulses. This must result from the selection effect discussed in §3.3; it is easier to identify more pulses when they are stronger. Table 16, columns (2)–(3) shows that even though there is no correlation between pulse amplitudes and the number of pulses for the initial simulated data, the fitting procedure introduces a strong positive correlation between these quantities; the tendency to miss low-amplitude pulses is greater in more complex bursts.

Figure 16 shows the distribution of pulse count fluences in the original simulations and in the fits to simulations. It shows that the fitting procedure has a strong tendency to miss pulses with low count fluences, similar to what we have seen for low-amplitude pulses.

Figure 17 and Table 16, columns (4)–(5) compare the number of pulses in each time profile with the count fluences of the individual pulses. They show no tendency for pulses to contain fewer or more counts in bursts with more pulses, in either the initial simulations (by design) or in the fits to simulations. Unlike pulse amplitudes, the tendency to miss low count fluence pulses appears to be independent of burst complexity. This differs from the results seen in the fits to actual bursts, where bursts containing more pulses tended to have pulses with lower count fluences (see Fig. 6 and Table 4, cols. [4]–[5]). This may

| VALUE FOR:       | AMPLITUDE | COUNT FLUENCE | WIDTH |      |
|------------------|-----------|---------------|-------|------|
|                  | $r_s$     | Probability   | $r_s$ | Probability | $r_s$ | Probability |
| Simulation ...... | $-0.04$   | 0.042         | $-0.02$ | 0.31    | 0.01 | 0.76        |
| Fit to Simulations | 0.22    | $7.1 \times 10^{-13}$ | 0.11 | 0.00068 | $-0.03$ | 0.36        |

Fig. 15.—Number of pulses per fit vs. pulse amplitudes of all pulses.

Fig. 16.—Distribution of pulse count fluences for all pulses from all bursts in initial simulations (solid histogram) and in the results of the fits to the simulated data (dashed histogram).
explain why the $2^{20}$ count limit for the TTS data was frequently reached before the 240 s time limit in the simulated bursts, but rarely in the actual bursts; the total count fluence increases linearly with the number of pulses in the simulated bursts, but less rapidly in the actual BATSE bursts.

**A3. PULSE WIDTHS**

Figure 18 shows the distribution of pulse widths in the original simulations and in the fits to simulations. The pulses in the fits to simulations tend to be slightly longer in duration than in the original simulations, but applying the Kolmogorov-Smirnov test to the two distributions shows that they are not significantly different; the probability that they are the same distribution is 0.39. This agrees with what we have seen in Figures 14 and 16, that the selection effects of the fitting procedure for pulse amplitudes and for pulse count fluences are similar.

Figure 19 and Table 16, columns (6)–(7) compare the number of pulses in each time profile with the widths of the individual pulses. They show no tendency for pulses to be wider or narrower in bursts with more pulses, in either the simulations or the fits to the simulations.

**Fig. 17.**—Number of pulses per burst vs. count fluences of all pulses.

**Fig. 18.**—Distribution of pulse widths for all pulses from all bursts in initial simulations (solid histogram) and in the results of the fits to the simulated data (dashed histogram).

**Fig. 19.**—Number of pulses per burst vs. widths of all pulses.
A4. TIME EVOLUTION OF PULSE CHARACTERISTICS WITHIN BURSTS

In the fits to actual BATSE data, it was found that pulse asymmetry ratios tended to decrease over the course of a burst (see Table 13). Table 17 shows the correlations between pulse asymmetry ratio and peak times within bursts for the simulations and the fits to simulations. It shows no tendency for positive or negative correlations in either the simulations or the fits to simulations.

| Value for:          | Decreasing | Binomial Probability |
|---------------------|------------|----------------------|
| Simulation .......... | 92.5/223 (41%) | 0.016                |
| Fit to Simulation   | 103/198 (52%) | 0.57                 |

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